University of Zurich[UZH]

Cognitive Psychology Unit

Properties and Mechanisms of the Focus of Attention in Working Memory

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Abstract

The focus of attention is a theoretical memory system component that selects representations for concurrent processing. In this thesis, I report a series of experiments that investigated the properties and mechanisms of empirical signatures of the focus of attention. When items are presented for study in a serial order, the last list item can be accessed quicker than any other item. This benefit has been taken as evidence that the last item is left in the focus of attention by default. I show that the benefit of the last item is not based on the same mechanism as the performance benefit obtained by selecting memory items by means of so called retro-cues, which prioritize an item for subsequent processing: Whereas the retro-cue benefit is driven by providing information about the cued item ahead of the test phase, the benefit of the last item may be a result of an unequal distribution of memory strength over list positions. Moreover, I demonstrate that the last list item is particularly vulnerable to visual interference presented after the study items. This observation is incompatible with the protective properties associated with the focus of attention. In contrast, cues can be used to protect items from such interference. These findings provide evidence that other than items selected by means of retro-cues, the last item does not represent an empirical signature of the focus of attention. Finally, I report evidence that retro-cues can be used to improve recall performance of all retained features of the cued feature-dimension. Taken together, the findings reported in this thesis highlight that the focus of attention is a flexibly applicable tool to select representations for complex cognition.

Zusammenfassung

Der Fokus der Aufmerksamkeit ist ein theoretisches Gedächtniskonstrukt, das Repräsentationen für kognitive Prozesse auswählt. In dieser Arbeit berichte ich eine Reihe von Experimenten, welche die Eigenschaften und Mechanismen des Fokus der Aufmerksamkeit untersuchen. Wenn Objekte, welche über kurze Zeit gemerkt werden müssen, nacheinander präsentiert werden, kann man am schnellsten auf das zuletzt gezeigte Objekt zugreifen. Dieser Vorteil wurde als Evidenz dafür interpretiert, dass das letzte Objekt automatisch im Fokus der Aufmerksamkeit ist. Die hier beschriebenen Studien zeigen, dass der Vorteil für das letzte Objekt nicht auf den gleichen Mechanismen beruht wie der Vorteil, der dadurch entsteht, dass man ein Objekt mit sogenannten Hinweisreizen für weitere Aktionen priorisiert: Während solche Hinweisreize Informationen über das gekennzeichnete Objekt bereits vor der Entscheidungsphase bereit stellen, entsteht der Vorteil für das letzte Objekt eventuell aufgrund einer ungleichen Verteilung von Gedächtnisstärke über die seriellen Positionen der Objekte. Desweiteren zeige ich, dass das letzte Objekt besonders anfällig für visuelle Interferenz ist. Dies steht im Kontrast zu der schützenden Eigenschaft, welche dem Fokus der Aufmerksamkeit zugeschrieben wird. Im Gegensatz dazu können Hinweisreize dazu benutzt werden, die Objekte vor solcher Interferenz zu schützen. Diese Befunde zeigen, dass im Gegensatz zu Objekten welche durch Hinweisreize identifiziert werden, der Vorteil des letzten Objekts keine Evidenz für den Fokus der Aufmerksamkeit darstellt. Ausserdem zeige ich, dass Hinweisreize benutzt werden können um den den Abruf für alle im Gedächtnis gehaltenen Merkmale einer durch Hinweisreize prioritisierten Markmalsdimension zu verbessern. Zusammengenommen unterstreichen die in dieser Arbeit berichteten Befunde, dass der Fokus der Aufmerksamkeit ein Werkzeug ist, welches sehr flexibel eingesetzt werden kann, um einzelne Repräsentationen für komplexe kognitive Arbeiten auszuwählen.

Contents

Part I Synopsis

1. Scope of the Work

Working memory is a system devoted to providing access to representations needed in ongoing cognitive tasks. Suppose you are visiting a bar with your friends Joe, Susan and Mary and you offer to go to the sales counter in order to buy some drinks. Working memory fulfils many functions that are required to complete this task successfully. Joe asks you to get him a small beer, Susan orders a glass of wine, and Mary would like to have a glass of water. This requires you to *select* relevant representations in long-term memory, *maintain* this information over a brief period of time, and create mnemonic bindings to associate your friends with their ordered beverages. Right before you get up, Joe tells you to bring him a large beer instead. His request requires you to *update* your memory for Joe's order. Moreover, Susan has changed her mind and would now like to have a soda drink instead of the wine. In working memory, you have to *remove* the glass of wine and add the soda drink to the binding associated with Susan. Finally, Mary emphasizes that you please not forget her order, as she is really thirsty. You therefore *prioritize* the representation of the glass of water in working memory. Updating, removal or prioritizing representations in working memory requires a mechanism that allows for selective access of memory representations. To fulfil this purpose, some theories of working memory assume a focus of attention as part of the working memory system (Cowan, 1998; Oberauer, 2002, 2009). The focus of attention is a theoretical selection device, which has the function to select an item as the input for a cognitive operation.

In this thesis I investigate the properties and mechanisms of the focus of attention in working memory. In the first study I show that two empirical signatures of the focus of attention are driven by distinct mechanisms. The second study provides evidence that not all prioritized items in working memory are protected from visual interference. Finally, in the third study I demonstrate that selective access to feature-dimensions of working memory representations can be used to improve recall precision of all retained features of the cued dimension.

1.1. The Focus of Attention and the Three Embedded Components Model

To describe hypothesized components and mechanisms of working memory, many conceptual architectures have been proposed that emphasize different features (for a review, see Miyake & Shah, 1999). In this thesis, I use a conceptualization of working memory that is based on three different functional states of information. Oberauer (2002, 2003, 2009) has proposed that working memory consists of three functionally distinct, embedded sets of representations: 1) the activated part of long term memory, 2) the region of direct access and 3) the focus of attention. Figure 1 depicts a conceptual architecture of this model.

All three levels are embedded in long-term memory, which is conceptualized as an associated network of representations. First, all currently activated representations constitute the activated part of long-term memory. Activation can be increased through perceptual input or through spread of activation from associated representations. For instance, when the current task requires the retention or manipulation of a few letters, activation for all letters of the alphabet is increased. Second, a subset of these activated representations is bound to a position in a common cognitive coordinate system, more specifically, items (e.g., color patches, words, shapes) are bound to contexts, establishing item-context bindings. A context is any information that can be used as a cue to selectively retrieve an item in memory, for instance the item's serial position in a list, its location in space, or a feature such as an object's shape or color. These item-context bindings constitute the region of direct access. Its function is to allow for quick access to a subset of representations. Finally, the function of the focus of attention is to select one[1] element among those currently held in the region of direct access for concurrent processing.

The term focus of attention is used in two different ways. In the embedded process model introduced by Cowan (1999), the focus of attention refers to a small number of about four items that are protected from forgetting through decay and interference. In this thesis, when using the term focus of attention, I will refer to a focus of attention that is characterized by its function to select representations within working memory - typically a single item (Oberauer & Hein, 2012) - for use in an upcoming cognitive

[1] see Oberauer and Bialkova (2009), Oberauer and Hein (2012) and Gilchrist and Cowan (2011) for a discussion on the capacity of the focus of attention.

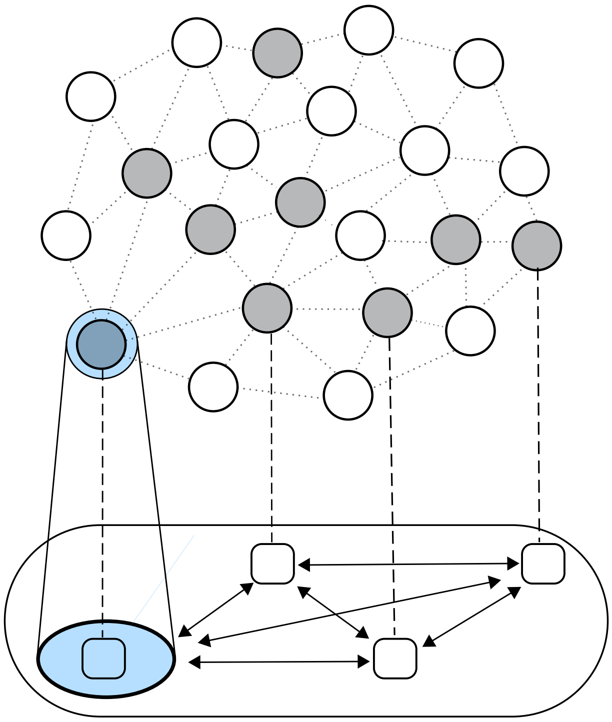

Figure 1: **Conceptual architecture of the three embedded components model of working memory**. Circles represent long-term memory representations that are associated with each other (dotted lines). Shaded circles are representations that are activated above baseline and represent the first functional state, the activated part of long-term memory. A subset of representations is bound to a context marker (squares) using item-context bindings (dashed lines). These item-to-context bindings constitute the region of direct access. Double arrows represent relations between items in the region of direct access. One item-to-context binding is selected by the focus of attention (blue overlay) for concurrent processing.

operation (Oberauer, 2003).

1.1.1. Computational implementations.

Computational models are an ideal tool to describe and test potential mechanisms involved in complex cognition (Farrell & Lewandowsky, 2010; Oberauer, 2013; Oberauer, Souza, Druey, & Gade, 2013). In this thesis, I attempt to describe the reported empirical observations within a framework of mechanisms implemented in a family of so called 2-layer neural network models (Burgess & Hitch, 1999; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Oberauer & Lin, 2017; Oberauer et al., 2013). Although the models differ in their detailed implementation, in their generic form, these models share a basic framework that is depicted in Figure 2. These models are built on two layers, one that represents the memory items (or "contents") and another layer that represents their contexts. Often, these layers use distributed, overlapping nodes, that is, item and context representations consist of patterns of activation across a large number of processing units. The two layers are fully interconnected by a matrix of connection weights (the *binding matrix*) and items are bound to a context by strengthening the connection weights between them (*item-context bindings*).

When items are presented serially, encoding proceeds primarily by associating the items with a context marker for its serial position. When items are presented simultaneously in different spatial locations, items are primarily bound to context markers of the spatial location. Retrieval is commonly initiated by activating a context marker in the context layer. This activation is forwarded to the item layer through the item-context bindings. The stronger the activation of the context or the item-context binding, the higher a bound item is activated in the item-layer. The exact nature of the decision process that governs whether a retrieved item is accepted as a response differs between the considered network models and task demands. Generally, the decision is based on the relative strength of activation of retrieved items in the item layer: The more an item is activated, the more likely it will be chosen as the response.

The generic structure of these neural-network models can be related to the architecture of the three embedded components framework of working memory (Oberauer, 2002). First, the activated part of long-term memory is reflected in increased activation of items in the item-layer. Second, the item-context binding matrix is the implementation of the region of direct access. Finally, the notion of a focus of attention refers to the item currently active in the item layer, together with its context currently active in the context layer (Oberauer, 2013; Oberauer et al., 2012; Oberauer & Lin, 2017).

1.2. Empirical Evidence for a Focus of Attention in Working Memory

Empirical evidence for the focus of attention within the region of direct access comes from four lines of research: Object-switch costs, visual search, the last-item benefit and the retro-cue benefit. Each phenomenon is quickly introduced and described. The first two studies reported in this thesis addressed the question whether the last-item benefit indeed represents an empirical signature of the focus of attention.

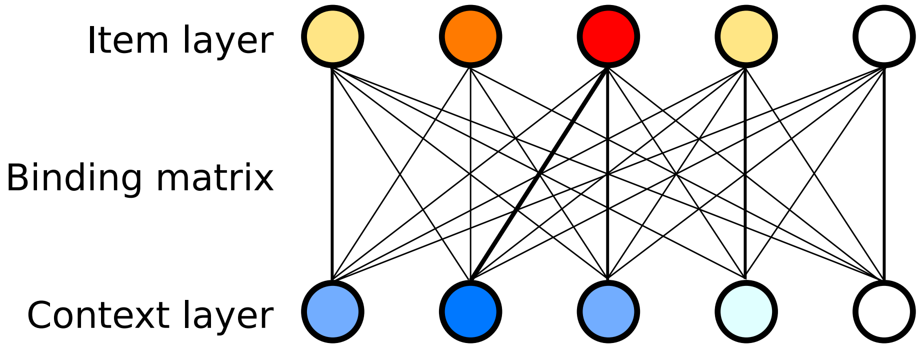

Figure 2: **Schematic illustration of a generic two-layer connectionist network**. Items are represented in the item layer and are conntected through connection weights to a context in the context layer. The strength of connection weights is represented through the thickness of the lines in the binding matrix. At retrieval, a context representation is activated. Due to overlapping context representations, several nodes are activated simultaneously. Shades of blue represent the amount of activation. In this example, the second context node is activated the most. This activation is forwarded through item-context bindings to the item layer, where items are activated to the extent that they are connected to the context activation (represented by shades of red). Because the third item-node is strongly connected to the most activated context-layer node, it is activated the most. The illustration is an adaptation of Figure 1 in Oberauer and Lin (2017).

1.2.1. Object switch costs.

The first line of evidence for the notion of a focus of attention in working memory comes from studies showing that switching between items in working memory for concurrent manipulation is associated with a cost. Specifically, object-switch costs describe the observation that when a cognitive operation in working memory requires access to a different item than what was accessed in the previous operation, the time it takes to complete a certain cognitive operation (such as a mathematical addition) is prolonged in comparison to when the same item is accessed twice in succession. For example, imagine participants are asked to retain two sets of numbers, say [1,2,3] and [3,4,5]. After people have retrieved the number three from the first set, object-switch costs manifest in quicker latencies for accessing the same number three from the first set, relative to any other number from the first set on the subsequent trial (Garavan, 1998; Oberauer, 2003; Oberauer et al., 2013). The effect can be explained by assuming that after completion of a cognitive operation, the just-processed item remains directly accessible in the focus of attention. Consequently, when the operation requires access to a new item, additional time is required to switch the focus of attention away. Moreover, after accessing the number three from the first set, people have been shown to be faster at accessing the numbers "4" or "5" relative to "3" from the second set ("item-repetition costs"; Oberauer et al., 2013). This finding indicates that what is selected by the focus of attention is the item's context, and not merely the item ("3") itself.

These findings have provided valuable insight into the mechanism of the focus of attention. To simultaneously account for object-switch costs and item-repetition costs, Oberauer et al. (2013) have implemented the following mechanisms in their network model: On the one hand, after completion of the operation, activation in the item layer is cleared, and the selected item's activation is even reduced. As a result, in the next trial access to this item is inhibited (item-repetition costs). On the other hand, the context layer activation is not completely cleared. As a consequence, some remaining context activation carries over into the next operation, and then reactivates the associated item in the item layer. Moreover, the item-context binding is strengthened every time it is used to access an item. As a result, when the same context is used as in the previous operation, item-context bindings are strengthened and the associated item can be accessed faster than any other item (object-switch costs).

1.2.2. Visual search template.

A second line of evidence supporting the notion of a focus of attention in working memory is the demonstration that a single item held in working memory guides visual search (for a review, see Olivers, Peters, Houtkamp, & Roelfsema, 2011). In visual search tasks, participants are instructed to look for a *target* among a number of distractors in a visual display. To know what to look for, people need to hold a representation of the target in working memory (a "search template" or "attentional set"). This representation can be compared with visual input until a stimulus matches. Crucially, it has been shown that people can only use one item as a search template (Houtkamp & Roelfsema, 2009). Arguably, it is the item selected by the focus of attention (Olivers et al., 2011).

1.2.3. Last item benefit.

A third line of evidence for the notion of a focus of attention in working memory is the observation that retrieval speed for the last item in a sequentially presented list is faster relative to any other item that has been previously presented (McElree, 2006). Arguably, the last item is held in the focus of attention, and can be compared to the probe immediately, whereas the other items first have to be retrieved into the focus of attention. To obtain a clear estimation of the speed of access to memory representations, McElree (2006) emphasized that it is crucial to use a measure that is independent of items' memory strength. Retrieval speed is a model-based measure that fulfils these requirements. It has been obtained by applying the so called response-deadline method to measure speed-accuracy trade-off (SAT) functions for retrieval of memory items in the classic Sternberg recognition task (Sternberg, 1969). The SAT function includes two parameters, the intercept δ and the rate β that provide a measure of retrieval-speed.

Response-deadline method and speed accuracy tradeoff functions. The time course of retrieval can be measured by experimentally varying the amount of time participants have available to make a recognition decision. In the response-deadline procedure, participants are instructed to give a recognition response immediately when a response signal is given. The point in time when the response signal is presented after probe onset is varied between a few hundred milliseconds and a few seconds. The pattern of accuracy growth over time that is derived from the response-deadline method can be described by the SAT function that is characterized by three periods (see Figure 3). An initial period of chance performance (1) is followed by a period of increasing accuracy (2) until an asymptote (3) is reached for the final period. These three phases are well captured by three parameters of the SAT function. The intercept parameter δ reflects the distinct point in time where the initial guessing period ends and information comes available. The rate parameter β denotes the rate at which information is accumulated, until the asymptote λ is reached. The intercept and rate parameter reflect the dynamic part of the SAT function, and they both determine the retrieval speed. Crucially, in contrast to response latencies obtained in regular recognition tasks, this model-based measure of retrieval speed is thought to be independent of the asymptotic strength of a representation, which is accounted for in the model by the asymptote λ parameter.

McElree's focus of attention. In their seminal study, McElree and Dosher (1989) demonstrated that the rate parameter β differed between serial positions (see Figure 3C for a depiction of this effect). Specifically, the rate was increased for the last item in comparison to all previously shown items, whose rates were statistically indistinguishable from each other. In other words, during the second period of the SAT function, the rate at which the probability of correct recognition responses increases with available response time, was shown to be uniquely faster for the last item.

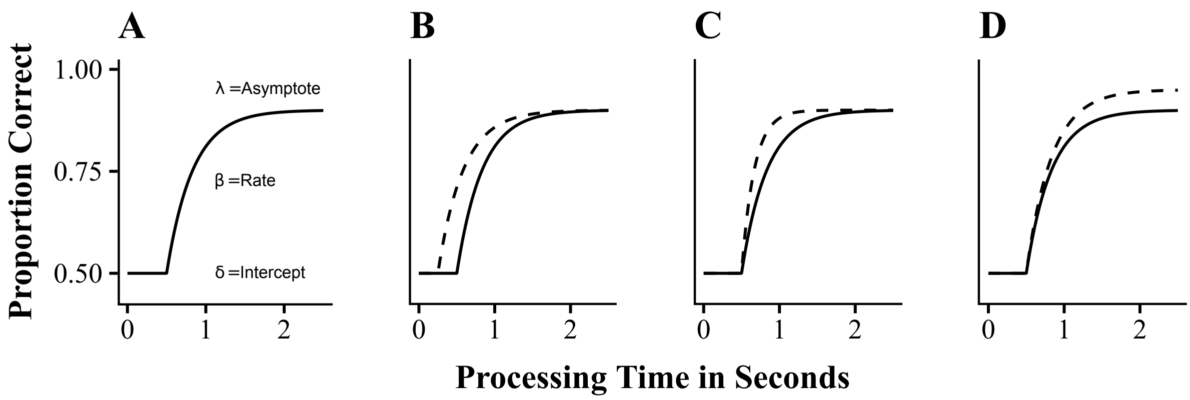

Figure 3: The time course of retrieval uncovered by by the response deadline method can be described with the exponential SAT function with three parameters: $\lambda(1-e^{-\beta(t-\delta)}), t > \delta$, else 0. **A)** Typical SAT curve. The processing time, which denotes the time from probe onset until a response is recorded, is depicted on the abscissa. A measure of performance, here proportion correct, is depicted on the ordinate. The intercept parameter δ reflects the distinct point in time where the initial guessing period ends and information comes available. The rate parameter β denotes the rate at which information is accumulated until an asymptote λ is reached. The dashed line shows the SAT function with a faster intercept parameter (**B**), with a higher rate parameter (**C**), and with a higher asymptote parameter (**D**).

This finding supported the conclusion that the last item is held in the focus of attention by default (McElree, 2006; McElree & Dosher, 1989). As the last item is held in the focus of attention, when the last item appears as a probe, it can be compared to its memory representation much faster than any other item that is not held in the focus of attention. Moreover, the view that the last-item benefit reflects not just any prioritized state in working memory, but in fact the focus of attention, is further supported by the finding that this benefit disappears when specific instructions directed rehearsal processes –arguably representing the focus of attention – towards early list items (McElree, 2006).

In the family of neural-network models, the last-item benefit is implemented by assuming that, by default, the last representation that was operated upon (in this example the last encoded item) remains activated, that is its context- and item-layer activation remains increased. Consequently, when the probe appears, the last list item can be accessed immediately. The results from our first study (see Section 1.3.1), however challenge these assumptions.

1.2.4. Retro-cue benefit.

A fourth line of evidence for the focus of attention comes from retro-cues. These are cues that are presented between the offset of the study list and the onset of the probe, and indicate the item that is most likely to be tested in a subsequent memory test. A validly retro-cued item can be accessed faster and more accurately in comparison to conditions where these cues are uninformative or invalid ("the retro-cue benefit"; Griffin & Nobre, 2003; Souza & Oberauer, 2016). Retro-cues are often of a spatial nature, that is they indicate the spatial location of an item, but they do not have to be: Feature-based (Heuer & Schubö, 2016; Pertzov, Bays, Joseph, & Husain, 2013) or even temporal (van Ede, Niklaus, & Nobre, 2016) cues have been shown to successfully provide access to representations for goal-directed behaviour. A key function of the focus of attention is dynamic selection of items in working memory for concurrent processing, and this is also what is accomplished by retro-cues. Therefore, retro-cues can be seen as a tool to direct the focus of attention (Souza & Oberauer, 2016).

Several explanations of the retro-cue benefit have been proposed (for a detailed review, see Souza & Oberauer, 2016), which can also be seen as potential mechanisms of the focus of attention. I now quickly summarize the four most important accounts.

Removal of irrelevant information. One proposed source of the retro-cue benefit assumes that information that is tagged as no longer relevant by a valid retro-cue can be removed from working memory. Removal of irrelevant information improves performance by reducing interference by superposition and through a reduction of confusion with irrelevant recall candidates (Oberauer et al., 2012). In the network model by Oberauer et al. (2012), removal of irrelevant information operates by reducing the strength of item-context bindings in the binding matrix.

Binding strengthening. Retro-cues may also be used to strengthen item-context bindings (Rerko & Oberauer, 2013). A crucial property of the retro-cue benefit is that it can be observed even when the focus of attention is shifted away from the cued item before the test phase (Myers, Chekroud, Stokes, & Nobre, 2017; Rerko & Oberauer, 2013; Rerko, Souza, & Oberauer, 2014). Neural network models account for this observation by assuming that the cued item-context binding is strengthened, and that this strengthening survives when another item is selected by the focus of attention.

Protection from interference. Improved performance for the retro-cued item may furthermore be driven by protection from visual input (e.g., a visual mask, the probe stimulus, or a color wheel) following encoding of the memory array which can otherwise replace or distort memory representations (Makovski, Sussman, & Jiang, 2008; Pinto, Sligte, Shapiro, & Lamme, 2013; Souza, Rerko, & Oberauer, 2016; van Moorselaar, Gunseli, Theeuwes, & Olivers, 2014).

Headstart of retrieval. Another proposed mechanism that improves performance is that retro-cues allow the cued item to be accessed (i.e. retrieved) before this information is used in the decision process (Souza et al., 2016) . This allows for the accumulation of better-quality information that is subsequently used in the decision process. In contrast, when no retro-cue is presented, the decision process is based on information that is distorted by other information, such as visual stimuli that are presented at test (e.g. the probe or distracting stimuli). In support of this notion, Souza et al. (2016) showed that performance can be increased when a delay was introduced that temporally separated retrieval and decision making processes. Their explanation for this benefit was that this delay had allowed participants to reduce the influence of misleading information before the retrieved information was used in the decision making phase. More support for the notion of a headstart of retrieval comes from a study by Shepherdson, Oberauer, and Souza (2017). The authors propose that for a recognition response, an item is in a first stage retrieved from working memory, before that item is compared to the probe to arrive at a recognition decision in the second stage. Evidence for this two-stage model came from the analysis of response-time distributions with the diffusion model (Ratcliff, 1978; Ratcliff & McKoon, 2008). Retro-cues were found to decrease the model's non-decision time parameter, which reflects the time that is required for non-decisional processes. In support of the head-start of retrieval hypothesis, they argued that the retro-cue effect on the non-decision time parameter reflects the retrieval of an item into the focus of attention before the probe is presented (Shepherdson et al., 2017).

1.3. The Last-Item Benefit And The Focus of Attention

In support of the notion that the last-item benefit reflects an empirical signature of the focus of attention, studies using instructed rehearsal (McElree, 2006) and refreshing (Vergauwe & Langerock, 2017) showed that the last-item benefit disappears when a different item is currently being rehearsed or refreshed. Moreover, Hu, Hitch, Baddeley, Zhang, and Allen (2014) reported that the last-item benefit decreases in favour of increasing performance for the first item, which was prioritized using task instructions.

This notion however has also been challenged (see Cowan, 2011, for a detailed criticism of behavioural and neuroscientific evidence). An item selected by the focus of attention is thought to be protected from visual interference (Cowan, 1999; Oberauer, 2002). In contrast to this assumption, Hu et al. (2014) showed that presenting interfering visual material after the serial presentation of the study list especially impaired performance for the last item, which shows that the last-item does not fulfil this proposed property of the focus of attention.

The first two studies reported in this thesis investigated the relationship between the empirical last item benefit and the theoretical notion of a focus of attention in working memory. Study 1 tested whether the last-item and the retro-cue benefit share the same mechanism. Study 2 investigated which prioritized states in working memory render items more susceptible to visual interference. The two studies converge to the conclusion that the last item cannot be seen as an empirical signature of the focus of attention in working memory.

1.3.1. Summary of Study 1.

My colleagues and I investigated whether the mechanisms involved in the last-item-benefit and the retro-cue benefit are identical (also see Section 3). We specifically tested the prediction that, if both effects are driven by the same mechanism, the retro-cue benefit should be attenuated when the retro-cue is directed to the item which already benefits from being presented last. If they shared the same mechanism, there would be nothing a retro-cue could add to the last item, as the mechanisms would already operate on it.

We addressed this hypothesis with a series of three experiments. In each experiment, we presented items in serial order and assessed participants' memory with a central (Experiment 1) or location-specific (Experiments 2 and 3) recognition probe. Serial presentation was thought to render the last item in the focus of attention (McElree, 2006). Moreover, in half of the trials we presented a retro-cue during the retention interval, which was thought to direct the focus of attention to the cued item (Oberauer & Hein, 2012; Souza & Oberauer, 2016). We measured SAT functions with the response-deadline method (see Section 1.2.3) in order to obtain a measure of retrieval speed.

Across three experiments, we found a consistent pattern of results in our SAT model based analyses. The last item had a credibly faster intercept parameter δ than earlier list items, whose intercept parameters could not be credibly distinguished (see Figure 3B for a depiction of an SAT curve with a faster intercept parameter). Moreover, retro-cued items were also associated with a smaller intercept than non-cued probes. The key result in all three experiments was that there was no attenuation of the retro-cue benefit for the last-item on this measure of retrieval speed. Rather, the last-item and retro-cue benefits on the SAT intercept parameter δ were additive. In other words, the benefit gained by retro-cueing an item in working memory was of the same magnitude regardless of whether the cue was directed to the item that already benefited from its last serial position, or to any other item which previously had not been in any prioritized state.

These findings provided evidence for at least two distinct forms of prioritization in working memory: the mechanisms involved in the selection through retro-cues can be differentiated from the mechanisms involved in the prioritization by virtue of the last serial position.

Mechanisms of the last-item benefit. Network models have accounted for the last-item benefit by assuming that, by default, the last-presented item together with its context, is in the focus of attention (Oberauer et al., 2012, 2013). Our results show that this mechanism is not an appropriate reflection of the engaged mechanisms. If indeed both the last-item benefit and retro-cue benefit arose from the fact that the context of item is already activated, we should have observed an attenuated retro-cue benefit for the last item, as the context for the last item would already have been activated regardless of the retro-cue.

Instead, these findings are compatible with the proposition brought forward by Donkin and Nosofsky (2012a). They proposed that the model-derived memory strength for serially presented items can be described by a power-law. Memory strength is high for the last item, drops drastically already for the second-to-last item, and then becomes (decreasingly) smaller with earlier serial positions. The observed pattern of results in Study 1 is compatible with the notion that the last-item benefit might simply reflect the extreme point of a continuous but steep recency gradient on the activation of the context and on the strength of the item-context bindings. Potential mechanisms that may be the source of this suggested pattern of memory strength involve (a) increased temporal distinctiveness of the last item, meaning the last item can be distinguished easiest from all other memory items because the temporal pattern renders it more distinct (Brown, Neath, & Chater, 2007), and (b) the lack of retro-active interference through subsequently presented stimuli for the last item (Allen, Baddeley, & Hitch, 2006; Cowan, 2011; Hu et al., 2014).

Mechanisms of the retro-cue benefit. The observed pattern of results for retro-cued items is in line with the retrieval head-start account of the retro-cue benefit (Souza et al., 2016, also see Section 1.2.4). In SAT curves, the intercept reflects the duration of any process preceding the decision process, because during that time no evidence in favor of either response accumulates. Accordingly, a retro-cue benefit on the intercept indicates that information was available sooner for retro-cued items. This interpretation is furthermore in line with the conclusion of Shepherdson et al. (2017) that argued that a retro-cue shortens the duration of a pre-decision process, which arguably reflects the retrieval of the relevant item from working memory.

At the same time, the pattern of results renders the strengthening hypothesis (Rerko & Oberauer, 2013, also see Section 1.2.4) less plausible as an explanation of the retro-cue benefit in our experiments. Although strengthened bindings improve access to representations, which is compatible with our findings of retro-cue benefits on retrieval speed, such strengthened bindings should also increase the quality of the information retrieved from working memory, and by implication, increase the rate of evidence accumulation, and improve performance at asymptotic levels. Yet, we found no evidence for retro-cue benefits on the rate or the asymptote parameter.

Asymptotic strength and possible computational implementation. Analysis of the asymptotic strength parameter of the SAT function showed that the last presented item reliably showed a higher asymptote parameter λ . In contrast, retro-cues did not improve the performance for cued items at long deadlines. Taken together with the main findings regarding retrieval speed of Study 1, these results indicate that the retro-cued item is actually retrieved ahead of time, that is, the item representation is reactivated in the item layer. Such a head start of the accumulation of evidence only implies that a particular asymptotic level is reached earlier and therefore is compatible with the finding that retro-cues did not affect asymptotic performance. Moreover, these results support the proposition that the last-item benefit reflects a recency gradient on the activation of the context and on the strength of the item-context bindings. Stronger item-context bindings for the last item imply not only faster retrieval but also better quality of the retrieved information, which is supported by the finding of higher asymptotic accuracy of the last item.

1.3.2. Protection from interference.

In order to fulfil its role as a selection mechanism in working memory, the focus of attention is thought to protect items engaged in concurrent processing from interference (Cowan, 1999; Oberauer, 2002). This view is supported by studies showing that retro-cued items, which arguably are held in the focus of attention, are protected from subsequent detrimental visual input, such as masks (Makovski & Jiang, 2007; Schneider, Barth, Getzmann, & Wascher, 2017; van Moorselaar et al., 2014) or the test display (Landman, Spekreijse, & Lamme, 2003; Makovski et al., 2008; Pertzov et al., 2013; Shepherdson et al., 2017; Souza et al., 2016).

To the contrary, other research has suggested that items that are arguably held in the focus of attention are particularly vulnerable to interference. Evidence for this comes from studies which have shown a disruption of memory performance by an irrelevant stimulus closely following the last list item (a suffix; Ueno, Allen, Baddeley, Hitch, & Saito, 2011; Ueno, Mate, Allen, Hitch, & Baddeley, 2011). In a series of experiments Hu et al. (2014) extended the suffix paradigm and presented the study items in sequential order, a procedure which is thought to leave the last item in the focus of attention (McElree, 2006). In some experiments they moreover introduced strategic incentives that either prioritized the first or the last list item (without changing the probability that a certain item is actually probed). Performance for the prioritized item was increased, supporting the notion that these items are held in a prioritized state in working memory. However, although participants were told that the suffix is redundant and can be ignored, its presentation impaired performance most particularly for these prioritized items. These results led Hu et al. (2014) to postulate that the last item, as well as items prioritized through strategy in response to incentives, reflect a common privileged state in working memory, akin to the focus of attention. Crucially, they claimed that given their pattern of results, the focus of attention combines high accessibility with increased vulnerability, a view which stands in sharp contrast to the assumptions of Oberauer (2002) and Cowan (1999).

1.3.3. Summary of Study 2.

I set out to investigate the contrasting set of findings regarding the susceptibility of prioritized items in working memory (also see Section 4). We examined which prioritized states in working memory are particularly susceptible to suffix interference, and more specifically, whether items prioritized by means of retro- and pre-cues are more susceptible to such interference, or rather, are protected from it.

To this end, we ran a series of four experiments, in which we combined the suffix procedure used by Hu et al. (2014) with the retro- and pre-cue paradigm. Participants studied four two-dimensional color-shape stimuli that were presented in sequential order in different spatial locations. We assessed participants' memory by presenting a one-dimensional probe (either a color blob or a color-less shape) and asking participants to recall the corresponding other feature (Experiments 4-6), or we cued the spatial location of an item and asked participants to recall the color and shape associated with this spatial location (Experiment 7). In half the trials, we presented an interfering suffix stimulus that contained the same features that were in the pool of possible colors and shapes as the study items. Critically, within each trial no feature of the suffix stimuli was shared with any of the four study items. We fully crossed the presentation of the suffix stimulus with the presentation of retro-cues (Experiment 4) or pre-cues (Experiments 5 to 7). This procedure thus was thought to leave several items in a prioritized state: On the one hand, items were thought to be prioritized by virtue of their last serial position, and on the other hand, items that were indicated by means of a pre- or retro-cue were also thought to be in a prioritized state.

In Experiment 4 we observed that the presentation of a suffix impaired memory performance regardless of the probe's serial position or whether the probed item was retro-cued. A possible concern of the experimental procedure was that the suffix was presented long after the offset of the last item. In order to rehearse or refresh memory representations (Baddeley, Baddeley, & Braddlely, 1986; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Johnson, 1992; Souza, Rerko, & Oberauer, 2015), or to resurrect representations from retroactive interference (Oberauer et al., 2012), the focus of attention might have shifted away from the last item by the time the suffix appears (see Donkin & Nosofsky, 2012b; Vergauwe & Langerock, 2017). In Experiment 5 we therefore presented the suffix shortly after the offset of the last item. Also, we externally guided prioritization with pre-cues instead of retro-cues. Yet, this procedure provided only inconclusive results. There was only anecdotal evidence for the claim that the last item is especially vulnerable to suffix interference and that pre-cued items are less vulnerable to such suffix interference. In Experiment 6 we then tried to move our suffix presentation procedure closer to conditions in which protection from visual interference for retro-cued items was observed in previous studies. Whereas Experiments 4 and 5 presented suffixes centrally, previous studies had shown that retro-cues can protect from interference from stimuli overlapping with the study items (Pinto et al., 2013) or from interference of the color in the color wheel spatially close to the probe (Souza et al., 2016). In Experiment 6 we thus presented suffixes that spatially overlapped with study items. Analyses yielded ambiguous evidence on whether a suffix spatially overlapping the memory items affect performance. Finally, in Experiment 7, the probed item was identified with a spatial-cue that was presented at the time of test, and we asked participants to recall both dimensions of the cued item. There was moderate evidence that the last-item is more susceptible to suffix interference than previous serial positions. Crucially, we found strong evidence that spatial pre-cues can be used to protect items, including the last item, from spatially overlapping, interfering stimuli.

The results from Experiment 7 are especially valuable for addressing the research question at hand. When no further guidance for prioritizing one or another item is provided, the last item was shown to be recalled best and this advantage came with an increased susceptibility to suffix interference. This supports the claim by (Hu et al., 2014) that prioritized items in working memory are more vulnerable to suffix interference[2]. However, we also showed that items that are validly pre-cued are protected from such suffix interference, including the last item. This finding demonstrates that not all prioritized items in working memory are especially susceptible to suffix interference (Hu, Allen, Baddeley, & Hitch, 2016; Hu et al., 2014).

[2] Additional analyses provided strong evidence that this pattern is also found across experiments when the neutral condition data from all four experiments was pooled.

Taken together, these experiments provide evidence that the last-item benefit and the retro-cue benefit reflect distinct privileged states in working memory. Items selected by the focus of attention are thought to be protected from interference (Cowan, 1998; Oberauer, 2002). Accordingly, the increased vulnerability of the last item supports the claim that the last item does not reflect the focus of attention in working memory (Cowan, 2011, see also Study 1 of this thesis), and the notion that the cued item is protected from such interference, supports the notion, that the retro-cued item indeed reflects the focus of attention in working memory.

Mechanisms of increased interference and protection. In general, suffix costs may be driven by superposition of the encoded suffix stimulus into the common weight-matrix, and by increasing confusions of recall candidates during retrieval (Oberauer et al., 2012).

Increased interference particularly for the last list item is an emergent side effect of overlapping context nodes in network models such as SOB-CS (Oberauer et al., 2012). When the suffix stimulus, presented after four study items, is accidentally encoded, it is naturally associated to a context marker for serial position 5. Because context markers for neighboring positions use overlapping nodes, when serial position is used as a retrieval cue to access a tested item, stimuli bound to neighboring serial positions will be cued as well. Therefore, to the extent that people use serial position as a retrieval cue to do the task, one should expect suffix costs to increase towards the last list item, because the context marker for serial position 4 (i.e. the last item) overlaps closely with the context marker for serial position 5, and as a result the suffix is retrieved most often for the last serial position.

Across individual experiments, analyses yielded both evidence for and against the notion of increased vulnerability for the last item. I speculate that this variability may reflect the fact that only in a small proportion of trials participants used serial position as a retrieval cue. Participants in Experiments 4-6 may have preferably recalled items by use of a direct color-shape binding, or in Experiment 7, by use of a spatial retrieval cue (Schneegans & Bays, 2017).

In Experiment 7 cues were shown to protect items from suffix interference. A plausible mechanism is that item-context bindings are strengthened by the cue, which renders them clearly retrievable after the suffix has been encoded into the common weight matrix, and as a result the retrieved item appears protected (Rerko & Oberauer, 2013; Souza et al., 2016).

1.3.4. Interim conclusion.

The investigation of retrieval dynamics and the vulnerability of the last item present a strong challenge to the notion that the last- item benefit is an empirical signature of the focus of attention. The last-item benefit does not represent a top-down selection process, but is more likely driven by the event sequence in the environment. Moreover, the last-item is especially vulnerable to the presentation of irrelevant visual stimuli, which is in contrast to the protective property associated with the focus of attention (Oberauer, 2002; Souza & Oberauer, 2016).

1.4. Dimensional Constraints of Selection in Working Memory

Using a lateralized electrical brain activity measure, the contra-lateral delay activity (CDA)[3], Töllner and colleagues demonstrated that retrieval of items from working memory, which is thought to involve the focus of attention, is influenced by the relation of feature-dimensions retained in working memory (Töllner, Eschmann, Rusch, & Müller, 2014; Töllner, Mink, & Müller, 2015).

In two studies, Töllner et al. (2014, 2015) presented a set of blue circles (denoted distractor items). Two of these items contained a specific feature (a color, a shape or an orientation), which distinguished these items from the set of blue circles. These were the two "memory items" that had to be remembered. The crucial manipulation was whether the two memory items differed on the same dimension (such as a red circle and a yellow circle) or on different dimensions (such as a red circle – sharing the shape feature with the distractors –, and a blue diamond – sharing the color feature with all distractors). The results showed that CDA amplitudes and reaction times were systematically affected by this manipulation. Reaction times were increased for items defined across two different relative to the same feature dimension[4].

[3] To obtain this neural measure, participants are asked to maintain stimuli presented on different hemifields of the screen. A positive recognition probe presented in the middle of the screen has been shown to be associated with a lateralized brain response, the CDA, contralateral to the location of where the probe that is currently retrieved from working memory had been presented during encoding (Dell'Acqua, Sessa, Toffanin, Luria, & Jolicœur, 2010; Eimer & Kiss, 2010; Kuo, Rao, Lepsien, & Nobre, 2009).

[4] Note that this effect was only found for set size 3 in Töllner et al. (2014) and was not statistically significant in Töllner et al. (2015).

Moreover, the CDA amplitude was higher for items defined across two different dimensions (Töllner et al., 2014, 2015), indicating that features of different dimensions are harder to remember than features from the same dimension.

1.4.1. Summary of Study 3.

In Study 3 (see Section 5), my colleagues and I examined the role of the cued feature-dimension on the retro-cue benefit, while keeping the dimensional composition of items retained in working memory identical (cf. Töllner et al., 2014, 2015).

In Experiment 8, participants were asked to study three colored arrows (i.e. all items included the same two feature dimensions, with different feature values). During the memory delay, participants were presented a dimension-based retro-cue. Specifically, either an informative retro-cue (the word "colour" or "angle") was presented that indicated with 75% validity which feature dimension was going to be probed, or a neutral retro-cue (the word "both") was presented that indicated that either feature dimension was equally likely to be probed. Retro-cues were informative for all items, and individual items remained equally likely to be probed. Participants were asked to reproduce either the color or orientation of one of the items on a continuous wheel. Analyses showed that providing information regarding a feature dimension during the retention interval improved the performance in the cued feature dimension at the expense of the uncued dimension.

In Experiment 9, the retro-cue indicated separately for each item which feature dimension would be tested, if that object would be probed (only two items were presented, each with a 50% chance of being probed). The critical manipulation was that both items would be cued either with regard to the same dimension, or with regard to different dimensions. Analyses showed that relative to a neutral condition where the cues provided no information regarding the to be probed feature dimension, retro-cue benefits were larger when the cued feature dimensions were the same rather than different.

Finally, in Experiment 10, we investigated whether selection of items in working memory has "global" effects on uncued features of the same dimension. We examined whether uncued items (i.e. items that are not selected by the focus of attention), are influenced by the cued dimension of the cued item. To this end, we applied a double cueing procedure. During the retention interval we presented a retro-cue that indicated for one of three items, which feature dimension would be tested if that item would be probed "early". In some trials, instead of probing "early" already after the first cue, a second retro-cue was presented that cued a feature-dimension of one of the two previously uncued objects in "late" trials. The dimension cued with the second retro-cue could either be same as (50%) or different from (50%) the dimension cued with the first retro-cue. The critical contrast for analysis was performance in late trials as a function of dimensional congruency between the second and the first retro-cue. We found that, at least for the colour dimension, performance was better for congruent relative to incongruent late trials. In other words, when participants were cued to recall the color of an item, but were then asked to report the color of a different item, they did so with higher precision than when they were asked to report the orientation instead. This indicates that selection in working memory had global influences, and activation was spread automatically to the colour representation of non-attended objects.

1.4.2. Tentative mechanisms of feature-dimension-based attention.

I propose that the reported effects of feature-dimensions are driven by an interplay of two types of context cues used for retro- cueing: During encoding, people associate all features to a spatial as well as to a non-spatial, "global", dimension context that is associated with the entire feature dimension (Oberauer & Lin, 2017; Oberauer et al., 2013). The spatial context enables access to both features of an object (also see Schneegans & Bays, 2017). In addition, participants use the dimension context to access the right set of features (i.e. the correct dimension).

When presenting dimension-based retro-cues such as "color" or "angle" (Experiment 8, also see Figure 14a), the dimension cue may be used to strengthen the bindings of the dimension context to all its associated features[5]. This increases the relative activation of the cued features in the item layer, and leads to improved precision when these features are reproduced.

Experiment 9 showed that simultaneously retro-cueing two objects with two different relative to two identical dimensions was less effective (also see Figure 15). I propose that when two feature-dimensions are cued, for each item participants access the cued feature by activating the spatial as well as the ap-

[5] Note that within the model framework of Oberauer and Lin (2017), this is mathematically equivalent to reducing the binding strength of the uncued dimension context and its associated features. Moreover, activation of all features of a dimension reflects detrimental background noise. In the here proposed mechanism, the combination of the dimension-context and the spatial context can be used to increase activation especially for the features retained in memory.

propriate dimension context cue. Activating the cued dimension context for one item automatically also increases activation for the feature of the same dimension of the other item. When the retro-cues indicate the same dimension for both items, this additional "spill-over" increases activation of the dimension that is being cued anyway. In contrary, when the retro-cues indicate two different dimensions, the spill-over increases activation for the uncued dimension. As a result, the gain in relative activation, which improves performance im comparison to the neutral condition, is higher for cues that are directed towards the same relative to two different dimensions.

Finally, Experiment 10 showed that reproduction of a feature is better when previously another item has been cued in the same relative to the other feature dimension (also see Figure 16). In the same fashion as before, I propose that when the first cued feature is accessed, activation of all features of the accessed feature-dimension is increased due to "spill-over" caused from the activation of the dimension context. As a consequence, when a feature of the dimension that was cued in the first place is probed, its reproduction benefits from higher relative activation.

2. General Discussion

The focus of attention in working memory is a theoretical construct that serves to select representations for concurrent processing. Across ten experiments, my colleagues and I investigated the mechanisms and properties of items that are arguably selected by the focus of attention in working memory, either by virtue of their last serial position, or by means of pre- and retro-cues. Study 1 showed that the retro-cue benefit can be best described as providing information ahead of time. Moreover, the mechanisms involved in improved performance for the last-presented item can be differentiated from the retro-cue benefit. Study 2 demonstrated that whereas the last list item is more susceptible to visual interference, items that are pre-cued, including the last item, can be protected from such interference. Study 3 revealed that retro-cues can be used to improve recall performance of all retained features of the cued feature-dimension.

The first two studies present a strong challenge to the notion that the last item in a list represents the focus of attention in working memory. Moreover, all studies show close relationships of the role of the focus of attention in working memory and perception. I will now discuss these overarching insights. In the course of the this work, several questions regarding the selection mechanisms in working memory emerged. I will furthermore address some of these open questions and sketch possible ways to investigate them.

2.1. The Last Item does not Reflect the Focus of Attention in Working Memory

Items *selected* by the focus of attention are thought to be protected from interference (Oberauer, 2002). In the reported studies, we found evidence that the prioritized state of the last item neither protects items from visual interference, nor does it reflect a top-down selection mechanism. Study 1 provided evidence that the last-item and retro-cue benefit are additive, and therefore the last-item benefit and the retro-cue benefit are unlikely to reflect the same mechanism. The last-item benefit may be a result of an unequal distribution of memory strength over list positions, which is to some extent independent of the person's goals. Study 2 showed that whereas the last item is more susceptible to visual interference than any other item held in working memory, a pre-cued item can be protected from visual interference. Taken together, we obtained two independent lines of findings that provide strong evidence to reserve the term focus of attention for cued items, but not for items that were presented last in serial order. This claim has implications for current theories of working memory.

Based on the notion that the last item shows increased retrieval speed, whereas all other items share a non-distinguishable retrieval speed, McElree (2006) has proposed an architecture of memory, according to which the only distinction of representational states in memory is between the item in the focus of attention, and passive memory representations. This contrasts with the view of the three-embedded components model, which postulates that working memory constitutes a separate entity embedded in long-term memory, which in addition to the focus of attention, includes items held in the activated region of working memory, and the region of direct access (Oberauer, 2002). In support of his architecture, McElree (2006) brought forward the argument that each state should be associated with its distinct retrieval speed. The finding that retrieval speed only shows a dichotomous pattern (McElree & Dosher, 1989), even for items in very long lists which exceed the capacity of working memory (Wickelgren, Corbett, & Dosher, 1980), supports his notion. In light of the results provided in Study 1, the observed dichotomous pattern may however in fact reflect a steep gradient on the activation of the context and on the strength of the item-context bindings, and not a top-down controllable selection device, such as the focus of attention. The observed dichotomous pattern of retrieval speed therefore does not represent "focal attention" (McElree, 2006, p.155).

The last-item benefit has been seen as an empirical signature of the focus of attention in the three-embedded process model of working memory (Oberauer, 2002; Oberauer & Hein, 2012). In light of the results reported in this thesis, this notion has to be updated. I propose that the last-item benefit does not represent the same representational state of items in working memory, that is associated with the focus of attention. The removal of this line of evidence does however not target the concept of a focus of attention within the region of direct access. Object-switch costs (Oberauer, 2003), the retro-cue benefit (Griffin & Nobre, 2003; Souza & Oberauer, 2016) and the biasing influence of a single item held in working memory on visual search (Olivers et al., 2011) still provide overwhelming evidence for the notion of a focus of attention in working memory.

The proposed distinction of the last-item benefit and the focus of attention has implications for the interpretation of effects that were associated with the focus of attention by means of the last-item benefit. Vergauwe and Langerock (2017) took the last-item benefit as an index whether the last item is in the focus of attention. The disappearance of the benefit was seen as support that the focus of attention has shifted to another item due to instructed refreshing. In light of the evidence presented in this thesis, I propose that the disappearance of the last-item benefit can still be taken as an index to assess whether refreshing has occured for another item, but for different reasons. Rather than assuming that the focus of attention moves from the last to the refreshed item, the disappearance of the last-item benefit may instead reflect the fact that the to-be refreshed item was retrieved (which may very well indicate that at this point this item is selected by the focus of attention), which implies that the last-item benefit disappeared because the context activation shifted from the last item to the refreshed item.

2.2. Parallel Characteristics of Selection in Perception and Working Memory

This thesis has unveiled two mechanisms of prioritizing information in working memory that parallel selection of information in perception. First, retro-cues are a flexible top-down controlled tool for selecting items for goal-oriented cognition and the last-item benefit reflects a more "bottom-up" prioritization, which is largely driven by the serial event sequence in the task. Such a distinction of prioritization mechanisms in working memory parallels the distinction of bottom up and top down mechanisms of prioritization in perceptual attention (Egeth & Yantis, 1997). Second, Study 3 showed that retro-cueing a feature in working memory affects all retained features of the same feature-dimension. Such top-down dimension-based influences parallel feature-dimension based attention modulations observed in perception (Gledhill, Grimsen, Fahle, & Wegener, 2015; McAdams & Maunsell, 2000; Müller, Reimann, & Krummenacher, 2003; Schledde, Galashan, Przybyla, Kreiter, & Wegener, 2016; Treue & Trujillo, 1999). Similarities of selection mechanisms in working memory and perception have spurred the view that they can be viewed as overlapping constructs (Gazzaley & Nobre, 2012; Kiyonaga & Egner, 2013). Indeed, perceptual attention has been shown to guide consolidation processes of information into working memory (Irwin, 1998; Schmidt, Vogel, Woodman, & Luck, 2002). Moreover, the item selected by the focus of attention in working memory has been shown to bias selection of stimuli in perception (Chan, Hayward, & Theeuwes, 2009; Hollingworth, Richard, & Luck, 2008; Olivers, Meijer, & Theeuwes, 2006; Olivers et al., 2011; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006). Vice versa, maintenance of information in spatial working memory has been shown to be impaired by shifts of spatial attention (Awh & Jonides, 1998; Awh, Jonides, & Reuter-Lorenz, 1998; Awh, Vogel, & Oh, 2006).

Despite their interactions, studies have shown that selection in working memory and in perception are separate mechanisms. Evidence for this notion comes from studies showing that the benefits of retro-cueing an item can also be observed when the perceptual focus of attention is shifted away from the spatial location of the cued item (Hollingworth & Maxcey-Richard, 2013; Maxcey-Richard & Hollingworth, 2013; Rerko et al., 2014; Souza & Oberauer, 2017). Moreover, Hedge, Oberauer, and Leonards (2015) showed that the locus of perceptual attention and selection in working memory can be guided independently in a spatial updating task: The locus of perceptual attention was controlled by changing the location of the arrow cue that indicated the next spatial updating step in working memory. Their results indicate that the mechanisms for selecting items in working memory do not require sustained perceptual attention. Moreover, effects of perceptual and memory-based selection were shown to be additive. When the locus of perceptual attention overlapped with the spatial location of the currently prioritized memory item, the times required to complete the updating task were faster in comparison to when the perceptual focus did not overlap with the focus of attention in working memory. This observed additivity provides evidence for the suggestion that these mechanisms may operate on a common framework (Postle, 2006; Theeuwes, Belopolsky, & Olivers, 2009).

2.2.1. Interactions in a common priority map?

Theeuwes et al. (2009) proposed that a shared priority map between perceptual attention and working memory serves to guide selection processes in both domains (also see Hedge & Leonards, 2013; Theeuwes, Olivers, & Chizk, 2005). The priority map can be seen as a spatial layout of the activation pattern in the item layer (Hedge et al., 2015). This means that the same activity in this map may on the one hand direct perceptual attention, and may on the other hand underlie maintenance and selection processes in working memory (Postle, 2006; Theeuwes et al., 2009). Hedge et al. (2015) laid out how such a shared priority map can account for interactions of selection in perception and working memory: When both perceptual and memory-based attention overlap, they increase activation for the same nodes in the item layer, which explains why these effects were found to be additive in their study.

Study 3 provided evidence that retro-cueing a feature affects all retained features from the same feature-dimension, which parallels feature-dimension based modulations in perception. One possible partial explanation for the similarity is that both of these modulations operate on the same common representational structure (such as a shared priority map or the item layer). I laid out a tentative mechanism for feature-dimension effects in working memory (see Section 1.4.2). I assume that participants can increase the relative activation of features with the use of a non-spatial dimension context cue that is associated with all features of a given dimension. Such a context marker is thought to be associated with all possible features of a dimension, and it can therefore be used to increase the activation of all its associated features. The same feature nodes might be targeted by feature-dimension based attention in perception (Müller et al., 2010): In short, Müller et al. (2010) propose that the saliency of different feature values is computed within dimensional input units, before this information is subsequently integrated in the saliency map. Crucially, the saliency information is weighted in a dimension-based manner prior to its integration in the saliency map, and this weight is modulated by bottom-up (such as repetitively looking for a target defined by the same dimension) and top-down processes. The greater the weight assigned to a certain dimension, the greater the rate at which evidence for a feature difference within this dimension accumulates at the saliency master map level. Although interactions between selection in working memory and perception have so far been primarily shown for spatial information held in working memory, if the priority map is indeed shared, the same interactions between perception and working memory processes are expected to be observed for other feature dimensions as well. For example, when a visual search task repeatedly requires the detection of a color stimuli, the dimensional weight of the color dimension in the priority map is thought to be up-weighted in a bottom-up manner (Müller, Heller, & Ziegler, 1995). The same up-weighting is expected when the color dimension is cued in a top-down manner (Müller et al., 2003). Future studies can address whether such feature-dimension based modulations in perception affect features of the same dimension held in working memory. In the given example, the notion of a shared priority map would be supported by showing that retention of the color-dimension in working memory is affected by these bottom-up and top-down modulations in perceptual attention.

2.3. Future Directions

2.3.1. Retrieval dynamics of updated items.

A major empirical finding supporting the notion of a focus of attention in working memory are object-switch costs (Garavan, 1998; Oberauer, 2003). In a similar vein as in the first study of this thesis, it remains to be investigated whether the mechanisms active in updating an item in working memory are also involved in the last-item and the retro-cue benefit.

Updating a memory representation involves the selection of an item in working memory, which implies that the context layer is used to cue the representation in the item layer. The peak of context activation must therefore be shifted towards the updated item. Moreover, in the context of an updating task, Oberauer et al. (2013) argued that after the updating operation is complete, the item activation is cleared, but some of the context layer activation is carried over into the next operation. Such increased leftover activation of the context-activation may induce a gradient on the context-cue. My colleagues and I have postulated in Study 1 that such a gradient on the context-cue is a major source of the last-item benefit. Consequently, when this gradient has shifted towards the updated item, I would expect that the last-item benefit disappears, when a different item than the last one has been updated, and that retrieval speed is improved for the updated item to the extent that context layer activation was carried over from the last operation. We have already run an experiment that attempted to address these predictions: In an unpublished study, we presented four numbers in sequential order before probing participants' memory by presenting a number in the middle of the screen for a recognition test with the response-deadline method. In half the trials, during the retention interval, participants had to add or subtract the number one from one of the items they retained in memory. The pattern of results that we obtained prevented us from drawing any conclusions regarding the disappearance of the last-item benefit: In the condition without any updating operation, there was no last-item benefit on retrieval speed parameters of the SAT function. This result rendered the comparison of the last-item benefit before and after updating operations of different serial positions meaningless.

In order to investigate whether the updating operation shares mechanisms with access to representations by means of retro-cues, the updating operation would have to be followed or preceded by a retro-cue, and this procedure needed to be embedded in a recognition task that allowed for the measurement of SAT curves. Given that the updating step provides no information regarding which item will be probed, there would be no information available that could feed into a headstart of retrieval when no retro-cue is presented. I therefore predict that in such a task, the retro-cue benefit will not be attenuated for an updated relative to an non-updated item.

2.3.2. Retrieval dynamics and vulnerability of other selection mechanisms.

A critical property of pre- or retro-cues is that they carry predictive value regarding which item will be probed. This allows for a headstart of retrieval of the cued item. By contrast, other selection mechanisms, such as directed refreshing (Vergauwe & Langerock, 2017), pay-off incentives (Hu et al., 2014), incidental cueing (Zokaei, Ning, Manohar, Feredoes, & Husain, 2014) and selection of an item for an updating operation usually do not indicate that the item they selected will also be more likely to be tested. Therefore, it is unlikely that these selection operations are also driven by a headstart of retrieval mechanism. Future studies should aim to describe the mechanisms of these selection operations and try to specify whether a particular mechanism is a reflection of a function of the focus of attention. To help with this classification, the vulnerability to interference of items selected by means of these mechanisms may be examined and incorporated into the decision. For example, Hu et al. (2014) showed that items that were prioritized by means of pay-off incentives also became more vulnerable to suffix interference. This is evidence for the notion that such pay-off incentives do not represent the focus of attention.

A crucial next step will be to investigate the vulnerability of just-updated items. Updating costs, which arguably reflect the shift of the focus of attention within working memory, are a landmark empirical signature of the focus of attention (Oberauer, 2003). According to this logic, these items should be less vulnerable to visual interference. If they however turn out to be especially vulnerable to interference, then either items selected by means of retro-cues are the primary empirical signature of the focus of attention, or the definition of the focus of attention will have to be changed, and the pre - and retrocue benefits may constitute a special instantiation of the focus of attention, which additionally protects items from interference.

2.3.3. Storage of different feature-dimensions.

Interference-based network models predict that retention of features of the same dimension is harder than retention of features of two different dimensions, because features of the same dimension are encoded in more similar item activations, which leads to more interference through superposition (Oberauer et al., 2012; Oberauer & Lin, 2017). This prediction contradicts the findings reported by Töllner et al. (2014, 2015), that demonstrated that access to features defined in the same feature-dimension is facilitated. Future studies should address this discrepancy with more measures. For example, interference through superposition is likely to distort the precision of representations. The use of the delayed-estimation procedure (Wilken & Ma, 2004) may therefore be more sensitive to reveal a benefit of storing features of different relative to the same dimension.

2.3.4. Familiarity and recollection.

In Experiment 2 and Experiment 3 we excluded intrusion probes from our analyses. Intrusions probes are interesting because they include two opposing sources of information. On the one hand, the presentation of an intrusion probe provides a context-free "familiarity" signal, that erroneously goes into the direction of accepting this probe. This information has to be overwritten by a context-based "recollection" signal that indicates that the intrusion probe is presented at a wrong spatial location (Oberauer, 2008; Oberauer & Lange, 2009).

Visually, it seems that with available response time, the propensity to accept a non-cued intrusion probe for some serial positions first increases, before it decreases and reaches a lower asymptote (see Figures 17 and 19). These dynamics are compatible with the notion that first a familiarity signal is accumulated, which is subsequently overwritten by a recollection signal (Göthe & Oberauer, 2008). Interestingly, it further seems that this bump (arguably driven by the familiarity signal) is absent for cued intrusion probes. Future studies could aim to model these patterns over time similar to Göthe and Oberauer (2008). They described the dynamics of a familiarity and a recollection signal with the SAT function. These processes were assumed to run in parallel, with familiarity having an earlier intercept than the recollection process. Future studies can address whether the recollection intercept parameter is slower for uncued relative to cued probes – reflecting a head-start of retrieval only of the item associated with this serial position –, whereas the familiarity intercept is not affected by the retro-cue.

2.4. Conclusion

The focus of attention is a theoretical construct that serves to select items retained in memory for concurrent processing, and can therefore be considered the workhorse of human cognition. This thesis revealed two important characteristics of the focus of attention. First, my colleagues and I have shown that there are multiple mechanisms that allow for an item to be accessed more quickly. On the one hand, the retro-cue benefit reflects a selection mechanism, which serves the main function of the focus of attention. On the other hand, the last-item benefit is a result of the unequal distribution of memory strength over list positions, which does facilitate access to representations, but is not directed by top-down goal-driven processes. This insight has provided a challenge to theories that have viewed the last-item benefit as an empirical signature of the focus of attention in working memory. Second, the focus of attention may not be limited to selecting individual items, but may also be able to select multiple features of the same feature dimension. This finding has tapped into a yet hardly investigated area in working memory and I have provided a tentative mechanism of dimension-based effects that can be tested with future experiments. Taken together, these findings emphasize the dynamic properties of the focus of attention that allow it to serve complex human cognition.

Part II Empirical Studies

3. A Cross-Eyed Focus of Attention in Working Memory: Additive Last-Item and Retro-Cue Benefits

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MN Review of the literature, design of the study, programming with Matlab, data collection, data analysis and interpretation, writing of the manuscript

HS Data analysis and revision of the manuscript

KO Design of the research question, supervision and discussion of MN's contributions, revision of manuscript.

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3.1. Abstract

The focus of attention can select and prioritize items maintained in working memory. We combined two empirical signatures of an item being held in the focus of attention. (1) The last-item benefit reflects increased retrieval speed to the item which was presented at the last serial position. (2) The retro-cue benefit refers to improved memory performance for an item in working memory that is prioritized using external cues during the retention interval. We investigated whether both phenomena result from the same mechanism. If that is the case, retro-cue benefits should be reduced when the retro-cue is directed to the item that already benefits from being presented last. We measured speed-accuracy-tradeoff functions with the response-deadline method to measure retrieval dynamics in a short-term recognition task. Across three experiments, we found no evidence for attenuated retro-cue benefits in retrieval speed when a retro-cue was directed to the last-presented item. The additivity of the last-item benefit and the retro-cue benefit points towards the co-existence of at least two distinct forms of prioritization in working memory.

3.2. Introduction

Working memory is a system devoted to the selective maintenance of information in a highly accessible state for processing in order to support cognitive activities such as reading, reasoning, and arithmetic calculations. Often, processing the contents of working memory requires selective access to a single element of the memory set - for instance when one element needs to be reported, updated, or used as input for a decision. Some theories of working memory therefore assume a focus of attention as part of the working memory system, which serves to select elements within working memory for processing (Cowan, 1998; Oberauer, 2003, 2009).

The term focus of attention is used in two different ways. In the embedded processing model introduced by Cowan (1998), the "broad" focus of attention refers to a small number of about four items that are protected from forgetting through decay and interference, and thereby form the core of working memory. Here, we will focus on a more "narrow" focus of attention that serves to select representations within working memory - typically a single item - for use in an upcoming cognitive operation (Oberauer, 2003). Evidence for the notion of such a single-item focus of attention comes from four experimental findings (for a review, see Oberauer & Hein, 2012): 1) the retro-cue benefit (e.g. Griffin & Nobre, 2003), 2) the last-item benefit (McElree, 2006), 3) object switch-costs (e.g. Garavan, 1998), and 4) evidence that usually only a single prioritized item in working memory guides visual search (Olivers et al., 2011). In this study, we are interested in the first two of these findings. We tested whether the retro-cue benefit and the last-item benefit result from the same mechanism of a single-item focus of attention. To this end, we merged the two paradigms, which allowed us to investigate both the retro-cue benefit and the last-item benefit at the same time.

Retro-cues are seen as a tool to direct the focus of attention to representations during the retention interval (Griffin & Nobre, 2003; Landman et al., 2003; Souza & Oberauer, 2016). In a typical retro-cue experiment, after presentation of a memory array, a cue identifies the location of one item that is most likely to be tested in a subsequently following recognition test. A validly retro-cued item can be accessed faster and more accurately in comparison to conditions where no cue, or an uninformative cue, is provided (Griffin & Nobre, 2003; Niklaus, Nobre, & Van Ede, 2017; Rerko & Oberauer, 2013; Souza & Oberauer, 2016; Souza, Rerko, Lin, & Oberauer, 2014; Souza et al., 2016; van Ede et al., 2016). The last-item benefit refers to the finding that when items are presented in serial order, retrieval speed for the last item is faster than for any other item. This observation has motivated the assumption that the last item is held in the focus of attention (McElree, 2006). Retrieval speed has been measured by applying the response-deadline method to measure speed-accuracy trade-off (SAT) functions for retrieval of memory items in the classic Sternberg recognition task. In the response-deadline method, participants are instructed to give a recognition response immediately when a response signal is given. By varying the point in time when the response signal is presented after probe onset (the deadline; e.g. from 100 to 1500 ms), accuracy can be measured as a function of time over the full time course of retrieval. The growth of accuracy over time that is derived from this procedure can be characterized by three periods. As the processing time before the deadline increases, an initial period of chance performance (1) is followed by a period of increasing accuracy (2) until an asymptote (3) is reached for the final period. In their seminal study, McElree and Dosher (1989) found that the rate at which the probability of correct recognition responses increases with available response time (during the second period) differed between serial positions. The rate was increased for the last item in comparison to all previously shown items, whose rates were statistically indistinguishable from each other. This finding supported the conclusion that the last item is held in the focus of attention by default (McElree, 2006). The rate of retrieval for an item in the focus of attention is increased because when the last item appears as a probe, it can be compared to its memory representation much faster than any other item that is not held in the focus of attention (McElree, 2006). The view that the last-item benefit reflects the focus of attention is further supported by the finding that this benefit disappears when specific instructions directed rehearsal processes towards early list items (McElree, 2006).

The notion that the last-item benefit reflects the focus of attention has been challenged (see Cowan, 2011). Donkin and Nosofsky (2012a) showed that the model-derived memory strength for serially presented items can be described by a power-law. Memory strength is high for the last item, drops drastically already for the second-to-last item, and then becomes (decreasingly) smaller with earlier serial positions. According to this proposition, the last item does not have a qualitatively different status from other items. Rather, the last-item benefit might simply reflect the extreme point of a continuous but steep power gradient on memory strength. Another finding questioning the proposition that the last-item benefit reflects the focus of attention is the last item's susceptibility to interference. Hu et al. (2014) showed that presenting interfering visual material after the serial presentation of the study list especially impaired performance for the last item. In contrast, research with the retro-cue paradigm has shown that a retro-cued item is protected from different kinds of visual interference (Souza et al., 2016; van Moorselaar et al., 2014).

In the present study, we present three experiments that directly test whether the last-item-benefit, as reflected in retrieval speed, and the retro-cue benefit are empirical manifestations of the same mechanism of a single-item focus of attention. We presented items in serial order and, after a brief retention interval, assessed participants' memory with a single recognition probe. The task of the participants was either to decide whether the probe was presented in the study list (Experiment 1) or whether the probe was presented at a particular position in the study list (Experiments 2 and 3). Serial presentation is thought to leave the last-presented item in the focus of attention by default. In half of the trials, we used retro-cues to direct the focus of attention to one of the list items during the retention interval. We used the response-deadline method to measure SAT functions, which allowed us to decompose the data into separate measures of retrieval rate and memory availability. This method allowed us to measure the last-item benefit specifically for retrieval speed, as described by McElree (2006). We used a hierarchical Bayesian model to assess the last-item benefit and the retro-cue benefit on parameters of the SAT model.

We tested the following predictions. If the increased retrieval speed found for the last item (i.e., the last-item benefit) and the retro-cue benefit reflect the same mechanism of the focus of attention, then a retro-cue directing the focus of attention to the last item should have a minimal effect at best, because the last item is already in a prioritized state (i.e. it is "in" the focus of attention) regardless of the cue. Under this assumption, the retro-cue benefit should be attenuated for the last item compared to the retro-cue benefit for earlier list items. In contrast, if the retro-cue benefit is a manifestation of a mechanism of the focus of attention that is different from what drives the last-item benefit, we should find additive effects of retro-cue and serial position. In other words, the retro-cue benefit should be as large when the retro-cue is directed to the last item as when it is directed to earlier items. To preview our main result, we found the two effects to be additive, warranting the conclusion that the last-item benefit and retro-cue benefit are not driven by the same mechanism.

3.2.1. Measurement model.

We now outline a hierarchical Bayesian measurement model that allows us to track changes in the time-course of retrieval of memory representations. We first describe the signal detection framework of the model. Then, we introduce the SAT function that captures the pattern of performance as a function of available processing time. Next, we describe how the model is embedded in a hierarchical-Bayesian framework. Finally, we discuss the advantages of this modeling technique in comparison to previously applied procedures.

Signal Detection Framework. Our memory task is a short-term recognition task in which participants are first presented with a list of (5 or 6) serially presented stimuli. Following a short retention interval, participants are presented with a single probe for which they have to make a memory decision. Participants have to accept positive probes (i.e., in Experiment 1 a stimulus that matches any of the items presented in the study list, and in Experiments 2 and 3 a stimulus that was presented in the same spatial location at test and in the study list) and reject negative probes. We denote accept responses to positive probes as *hits* and accept responses to negative probes as *false alarms*.

We use a signal detection framework (e.g. Kellen & Klauer, 2016; Macmillan, 2002) to relate hits and false alarms in a principled manner to obtain independent measures of memory performance and response bias. We assume that the presentation of positive and negative probes evoke memory signals whose distributions can be described by a normal (i.e., Gaussian) distribution with variance 1, and mean μ_N for the negative probes, and mean μ_P for the positive probes. At test, participants compare the memory signal of the probe against a fixed response criterion, c. If the memory signal of the current probe is larger than c, the probe is accepted, and rejected otherwise. In mathematical terms this corresponds to the following predictions:

$$P(accept|positive\ probe) = P(hits) = \int_c^\infty \mathcal{N}(\mu_P, 1), \tag{1}$$

$$P(accept|negative\ probe) = P(false\ alarms) = \int_c^\infty \mathcal{N}(\mu_N, 1), \tag{2}$$

where $\mathcal{N}$ is the probability density function of the normal distribution. Given the properties of the normal distribution, this can be simplified to

$$P(hits) = \phi(\mu_P - c), \tag{3}$$

$$P(false\ alarms) = \phi(\mu_N - c), \tag{4}$$

where ϕ is the cumulative distribution function of the normal distribution. Above-chance performance is obtained if $\mu_P > \mu_N$. The distance between the two distributions,

$$d' = \mu_P - \mu_N, \tag{5}$$

is a common measure of memory performance or *sensitivity* that is independent of response bias.

Moreover, the parameterization of c is such that positive values indicate a response bias towards rejecting a probe and negative values a response bias towards accepting a probe.

Performance dynamics and the SAT function. To account for the full time course of retrieval as uncovered by the response deadline method, we describe the increase in sensitivity over time with the exponential SAT function with three parameters,

$$\left.\begin{array}{l}\mu_P(t)\\[1em]\mu_N(t)\end{array}\right\} = \lambda(1 - e^{-\beta(t-\delta)}), t > \delta, \text{ else } 0, \tag{6a}$$

$$d'(t) = \lambda(1 - e^{-\beta(t-\delta)}), t > \delta, \text{ else } 0, \tag{6b}$$

where the processing time t is the duration from probe onset until the response is recorded. For reasons explained below, in Experiment 1 we estimated a separate set of SAT parameters for both μ_P and μ_N (Equation 6a), and in Experiments 2 and 3 we estimated one set of SAT parameters and restricted $\mu_P = d/2$, and $\mu_N = -d/2$ (Equation 6b). With these parameterizations our model accounted for both hits and false alarms. The SAT function has been shown to adequately summarize the retrieval dynamics in response-deadline tasks (McElree, 2006; McElree & Dosher, 1989; Wickelgren et al., 1980). The parameters of the SAT function reflect the above mentioned three phases of retrieval. First, participants perform at chance level because at short processing times no information is available to them. The intercept δ denotes the point in time where information first becomes available and performance departs from chance. Second, β reflects the rate at which sensitivity grows with increasing processing time. The intercept and rate parameter jointly describe retrieval speed. These measures are independent of the probability of eventually recalling a memory representation, which is captured by the third parameter, the asymptote λ, which reflects the sensitivity level reached in the last period.

Hierarchical bayesian framework. The signal-detection SAT model was implemented in a hierarchical-Bayesian framework (Gelman et al., 2014). In a Bayesian framework, one's information regarding the parameters is specified by probability distributions. The state of ignorance before any data is collected is represented via *prior distributions* (or *priors*). These priors are then updated in light of the data using

Bayes' theorem. The resulting new state of knowledge, the *posterior distribution*, can be used for statistical inference. Here, we employed an efficient version of Hamiltonian Monte Carlo to obtain samples from posterior distributions (Carpenter et al., 2016).

For each experimental condition of interest[6], we obtained posterior distributions for the three SAT parameters, δ, β, and λ. The posterior distributions represent the probabilities of the parameters conditional on data and model (where the latter includes the prior) and thereby directly allow statistical inference (Gelman & Hill, 2007). To assess the difference between parameters of two conditions, we simply subtracted the posterior distribution of the to-be-compared conditions from each other to obtain a posterior distribution for their difference. For ease of interpretation, we always subtracted the distribution of the smaller parameter value from the distribution of the larger parameter value. In this way, between 0% and 50% of the posterior difference distribution lies below zero. The smaller the proportion below zero - or the larger the proportion above zero - the stronger the evidence for a difference between the two conditions. To gauge the strength of evidence for a difference, we calculated p_B as the proportion of the difference distribution below zero, multiplied by two. This makes p_B a statistic that ranges from zero to one, with values near zero denoting evidence for a difference, and values near one indicating that equal mass of the posterior difference distribution extended below and above zero. Values near one therefore provide some evidence against a difference.

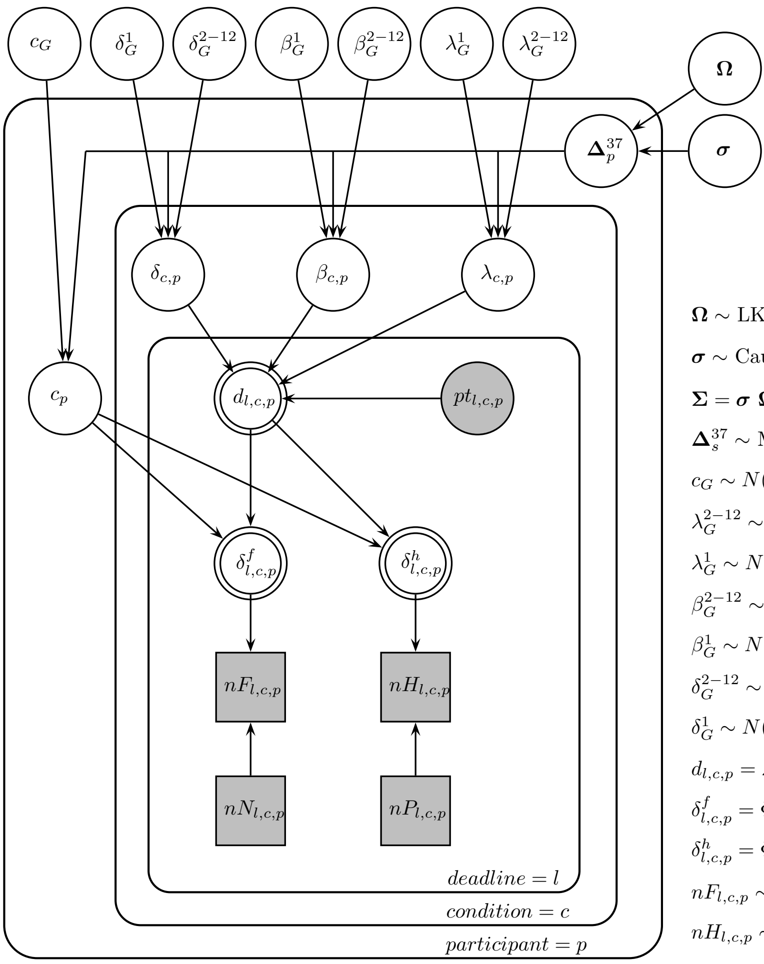
To adequately account for both inter-individual and intra-individual variability, we implemented the model in a hierarchical fashion using so-called partial pooling (Gelman & Hill, 2007). Individual parameters were assumed to come from group-level distributions. We assumed normal group-level distributions for all three SAT parameters, as well as for the signal detection criterion. In addition, we estimated the full variance-covariance matrix among all parameters [i.e., the group-level distribution was multivariate normal;](Klauer, 2010). Note that all statistical inference is performed on the group-level parameters. A graphical model of the hierarchical-Bayesian implementation of the signal-detection SAT model is depicted in Figure 4. We used either non-informative priors (a so-called LKJ-prior with scale 1 for the correlation matrix of the multivariate normal distribution) or weakly informative priors

[6] Serial position and cue condition were considered conditions of interest. The response deadline lag, although experimentally manipulated, was not, as it was part of the SAT function and thereby already accounted for in the model.

with most of their mass on reasonable parameter values (following Gelman et al., 2014). To account for differences between conditions, we estimated separate SAT parameters for each experimental condition of interest, but only one overall signal-detection criterion c (i.e., c did not vary across conditions).

Advantages of the present modeling approach. Previous SAT studies have commonly fitted the SAT function to estimates of d′ of each individual participant, before individual parameter estimates or model performance indices were averaged. The crucial conclusions were then drawn from comparing a set of models using model performance indices (Liu & Smith, 2009; McElree, 2006; McElree & Dosher, 1989; Mızrak & Öztekin, 2016a, 2016b; Öztekin & McElree, 2010). For example, in the seminal study by McElree and Dosher (1989), the authors compared a model with the same rate for all serial positions, a model with two rates - one for the last position and one for all previous positions - and a model with a separate rate for each serial position. Among these three models, the second (with 2 rate parameters) provided the best account of the data (i.e., highest adjusted-R^2). The same pattern of results was found when effects of serial position were modeled on the intercept parameter. (The rate model was chosen as the winning model because its overall performance in terms of adjusted R^2 was slightly better than when the effects were modeled on the intercept parameter.) In this model-selection procedure, only a limited set of models has been considered (but see Mızrak & Öztekin, 2016b). For instance, it was not tested whether a model that assigns the second-to-last and last item an increased rate would fare better than any of the other models. Such comparisons, however, are crucial to investigate the nature of the last-item benefit. If the last-item benefit is unique to the last item (McElree, 2006), retrieval rate should show a dichotomous pattern with only the last item showing an increased rate. In contrast, if the last-item benefit represents the peak of a steep power gradient of memory strength (Donkin & Nosofsky, 2012a), the second-to-last item could also show a higher rate than any earlier item.

The present approach improves on this procedure in several regards. First, in contrast to the classical approach in which d' is calculated in a first step and the SAT function is applied to the calculated d' in a second step, we estimate the signal-detection model and the SAT function in one step, which avoids the accumulation of estimation error. Second, our model avoids arbitrary corrections for hit-rates or false-alarm rates of zero or one, which are necessary to compute d' using the classical approach (Stanislaw



$\boldsymbol{\Omega} \sim \mathrm{LKJ}(1)$

$\boldsymbol{\sigma} \sim \mathrm{Cauchy}^{+}(0,4)$

$\boldsymbol{\Sigma} = \boldsymbol{\sigma}\ \boldsymbol{\Omega}$

$\boldsymbol{\Delta}_s^{37} \sim \mathrm{MvNormal}(0, \boldsymbol{\Sigma})$

$c_G \sim N(0,1)$

$\lambda_G^{2-12} \sim N(0,1)$

$\lambda_G^1 \sim N(4,1)$

$\beta_G^{2-12} \sim N(0,1)$

$\beta_G^1 \sim N(2,1)$

$\delta_G^{2-12} \sim N(0,1)$

$\delta_G^1 \sim N(0.3, 0.1)$

$d_{l,c,p} = \lambda_{c,p} * \left(1 - e^{-(pt - \alpha_{c,p}) * \beta_{c,p}}\right), pt_{l,c,p} > \alpha_{c,p}, else\ 0$

$\delta_{l,c,p}^f = \Phi\left(-\frac{1}{2} d_{l,c,p} - c_p\right)$

$\delta_{l,c,p}^h = \Phi\left(\frac{1}{2} d_{l,c,p} - c_p\right)$

$nF_{l,c,p} \sim \mathrm{Binomial}\left(nN_{l,c,p}, \delta_{l,c,p}^f\right)$

$nH_{l,c,p} \sim \mathrm{Binomial}\left(nP_{l,c,p}, \delta_{l,c,p}^h\right)$

Figure 4: Graphical depiction of the hierarchical Bayesian SAT model. Observed variables are represented by shaded nodes. Discrete variables are displayed as squared nodes and continuous variables are displayed as circular nodes. Deterministic nodes have a double border. The direction of arrows indicates that the node at the end of the arrow depends on the node at the start of the arrow. Plates visualize the hierarchical structure in the data. Subscripts denote different conditions, superscripts denote the length or index of vectors. N is the probability density of the normal distribution. *MvNormal* is the multivariate extension of N. ϕ is the cumulative distribution function of the normal distribution. nF and nH are the number of false-alarms and hits, respectively. nN is the number of negative, and nP the number of positive probes.

& Todorov, 1999). Third, a Bayesian statistical approach provides us with full posterior distributions, which allows us to assess the precision of the estimates in a direct manner. Fourth, a general property of hierarchical models is that individual and group-level parameters are estimated simultaneously using partial pooling. The estimation of each individual parameter is informed by the data of all participants because all data are used to estimate the group-level parameters, which at the same time provides a soft constraint for the individual-level parameter estimates. The crucial benefit of this procedure is that both the group-level parameters and the individual-level parameters are estimated more precisely because unrealistic or extreme individual parameter estimates have been constrained (Katahira, 2016).

One further difference between the current approach and the previous approach is that we did not base our inference on model comparison, but on parameter estimates within one encompassing model in which all parameters were allowed to vary freely across conditions. The reason for this choice is two-fold. First, given the large space of all possible models (i.e., all possible partitions resulting from the number of serial positions times two for the cue conditions, for each of the 3 SAT parameters), an exhaustive exploration of the full model space is comparatively expensive. Second, penalized model fit indices that rely on counting the model parameters such as adjusted-R^2, AIC, and BIC, were developed in the context of linear models (Burnham & Anderson, 2003) and assume that each parameter has an approximately equal influence on the complexity of the model. This assumption is at least questionable for a nonlinear model such as the SAT. A principled model comparison within a Bayesian framework requires calculating the Bayes factor for each pairwise model comparison, which we found not to be feasible with current methods.

3.3. Experiment 1

In our first experiment we employed a Sternberg task merged with a retro-cue paradigm. In the study phase participants had to remember a list of six words. Presentation occurred in serial order in six spatial locations located along a virtual circle. After a brief period of time, participants were asked whether a centrally presented probe matches any of the words presented during the study phase. In half of the trials, a spatial retro-cue indicated the word that will be probed in a positive trial. Participants' processing times were manipulated using a response-deadline method, allowing us to track the full time course of retrieval. The data and the analysis scripts for all experiments can be accessed in the Open Science Framework (https://osf.io/6apd9/).

3.3.1. Method.

Participants. We recruited 16 volunteers (13 females, mean age = 23) through the University of Zurich participant volunteer pool who participated in eight 1h test sessions. They completed one or two training sessions beforehand to acquaint themselves with the response-deadline method. No further practice trials were run in the test sessions. Participation was reimbursed with 15 Swiss Francs per session. Due to technical problems, we could not record data from one session of one participant. We excluded one participant from the analysis due to below-chance performance even at long response-deadline lags[7].

Materials. For each trial, we took a pseudo-random subset of words from a word list which was comprised of a set of 639 one- or two-syllable German nouns consisting of four to five letters. The sampling algorithm ensured that neither one of the six study words, nor a negative probe word, had appeared in any of the previous three trials. The experiment was programmed and run in MATLAB using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

Design. Each test session consisted of a total of 432 trials resulting from three complete permutations of twelve response-deadline lags, six serial positions of items matching the probe (for positive probes), and whether the probe had appeared in the study phase (positive probe) or not (negative probe). The trials were presented in random order. The presentation of a retro-cue (cue condition) was varied across odd and even sessions. Nine participants began with a session with retro-cues, and eight participants with a session without retro-cues. Across eight test sessions, this design yielded a total of 12 trials for each combination of response-deadline lag, serial position, and cue condition for a positive probe, and 72 trials per response-deadline lag and cue condition for negative probes (which cannot be associated

[7] This participant probably confused the response keys. The pattern of results does not change when the data is recoded and included in analyses.

with a serial position).

Procedure. Each trial began with the presentation of six blue frames (visual angles with a viewing distance of 50 centimeters: width = 8.5°, height = 6.7°), equally distributed on a virtual circle (diameter = 23°) on grey background for 1000 ms. Frames remained on the screen for the entire trial. Then, six words were presented, one in each frame, with a presentation time of 450 ms and an inter-stimulus-interval of 50 ms. Presentation occurred in serial order along the virtual circle in clock-wise direction starting from the frame that was located at the top of the screen. After presentation of the last word, the empty frames were shown for 500 ms.

The sequence of events that followed depended on the cue condition. In the retro-cue condition, an arrow was presented for 500 ms that indicated with certainty the word that would match the probe if the probe was positive. Then, after a 500 ms post-cue interval, the test probe was shown in the center of the screen. In the no-cue condition, the test probe was presented immediately, such that the retention interval matched the pre-cue interval in the retro-cue condition. These timings were chosen to rule out a decay-based explanation of the retro-cue benefit (Rerko & Oberauer, 2013).

Participants indicated whether the probe matched any word of the study set ("accept" responses were indicated with the "j" key, "reject" responses with the "f" key). The probe appeared for a variable length of time, depending on the response-deadline lag. At 100, 121, 164, 227, 312, 481, 545, 693, 864, 1054, 1267 and 1500 ms after onset of the probe, the probe disappeared from the screen, and participants were cued by a tone (duration = 50 ms, frequency = 2000 Hz, played over headphones) to immediately respond[8]. Participants were instructed to respond within 270 ms regardless of their ability to make a correct response. They received visual latency feedback, which provided their response time as well as written feedback in the form of "schneller antworten" (respond more rapidly) for latencies above 270 ms, "Bitte antworten Sie erst nach dem Tonsignal" (please respond only after hearing the auditory cue) for anticipated responses with a response latency below 100 ms, and "Rechtzeitig" (in time) for responses within the accepted time window. Each trial was initiated by pressing the space bar.

[8] Actual presentation times may have varied slightly due to the 60 Hz refresh rate of the monitor.

3.3.2. Results.

Response latencies. We considered trials with a response time below 100 ms as anticipations or motor errors. Trials above 500 ms were likely due to attentional lapses undermining the response-deadline method. We therefore excluded extreme trials with response latencies above 500 ms or below 100 ms from analyses (2.35%).

To verify that participants obeyed to the deadline response instructions, we investigated their response times. After exclusion of extreme trials, and averaged across participants and experimental conditions, participants met the response-deadline criterion (< 270 ms) in 92.9 % of all trials. To account for different response latencies across conditions and participants in our model-based analysis, we created a new variable called processing time by adding the mean reaction time per individual and condition cell to the response-deadline lag of this specific condition.

Model-based analysis. Due to the central presentation of probes, non-cued new probes cannot be associated with any serial position. To account for this, we analyzed the data with a model that estimates the means of the signal distributions, and consequently the SAT parameters, for positive and negative probes separately.

$$\mu_P = \lambda_{pos}(1 - e^{-\beta_{pos}(t-\delta_{pos})}), t > \delta_{pos}, \text{ else } 0, \tag{7}$$

$$\mu_N = \lambda_{neg}(1 - e^{-\beta_{neg}(t-\delta_{neg})}), t > \delta_{neg}, \text{ else } 0, \tag{8}$$

As a consequence, we will report credible differences of the three SAT parameters between experimental conditions of interest separately for positive and negative probe trials (results of negative probes are reported in Appendix A.1).

The model was estimated in Stan through R (R Core Team, 2014) using rstan (Carpenter et al., 2016). After discarding 1,000 warmup samples, we retained 3,000 post-warmup samples for each of 4 independent chains. Convergence statistics indicated good mixing behavior with $\hat{R} \leq 1.01$ for all estimated model parameters (Gelman & Rubin, 1992). Visual inspection of MCMC trace plots of the group-level parameters indicated the same. The number of effective samples was above 600 for all estimated model

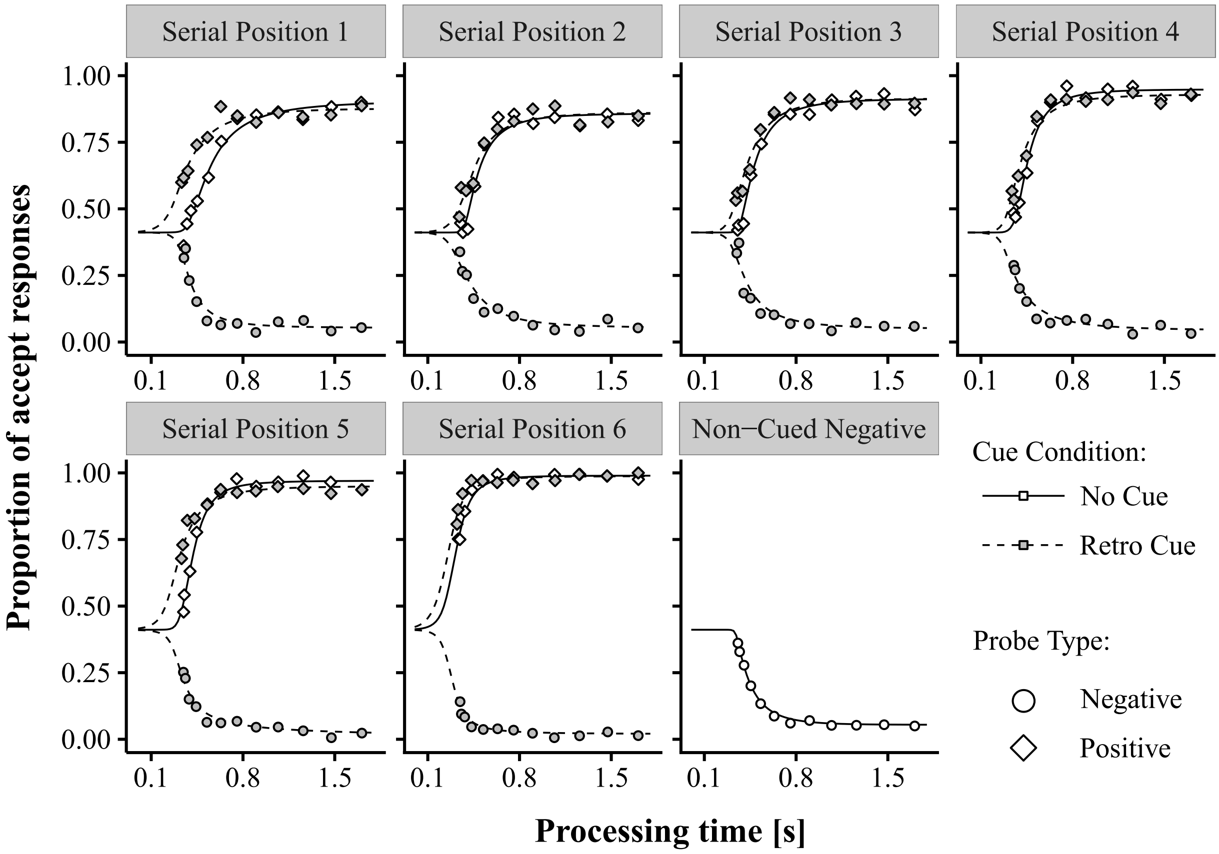


Figure 5: Observed (symbols) and predicted (lines) group-level proportion of accept responses for positive (diamonds) and negative (circles) probes for each serial position and cue condition as a function of processing times. Filled objects connected through a dashed line depict retro-cued probes whereas non-filled objects connected through a solid line depict non-cued probes. Non-cued negative probes cannot be associated with a serial position and are depicted in their own panel.

parameters.

Model fits are depicted in Figure 5, which compares the median of the model predictions generated from the posterior distribution (the lines) to the observed proportions of "accept" responses (the dots), for positive and negative probes separately. Visual inspection of the model fit shows that the model accounted well for the retrieval dynamics of all experimental conditions. Median[9] parameter values and the results from all pairwise comparisons among conditions for each parameter for the positive probes are reported in Table 1. We also provide the 95% credible interval (CI), which describes the area between the 2.5th and 97.5th percentile of the posterior distribution, for each SAT parameter.

[9] The median of the posterior distribution.

Positive trials last item benefit. The last-item retrieval speed benefit is expected to be expressed in an advantage of serial position 6 in comparison to serial positions 1-5 in either the intercept or rate parameter, or both (McElree, 2006; McElree & Dosher, 1989). For the rate parameter we found no credible pairwise differences between any of the conditions (see Table 1). Thus, we focused on comparing conditions of the intercept parameter.

To test the last-item benefit, we compared the mean intercept for serial positions 1 to 5 with the mean intercept for serial position 6 across retro-cued and non-cued probes. This comparison revealed that serial position 6 had a credibly smaller intercept ($p_B < .001$, median benefit = 120.0 ms [95% CI = 67.8, 181.1]). The last-item benefit was also observed when we compared the mean intercept for serial positions 1 to 5 with the mean intercept for serial position 6 separately for non-cued probes ($p_B < .001$, 137.9 ms [85.5, 208.1]) and for retro-cued probes ($p_B = .02$, 99.7 ms [13.1, 201.8]). For comparison, in an experiment that presented only non-cued probes, McElree and Dosher (1989) reported a somewhat smaller last-item benefit of 74 ms on the intercept parameter.

We additionally investigated all pairwise comparisons between serial positions for each cue condition as shown in Table 1. For non-cued probes, the intercept for serial position 6 was smaller than each of the intercepts of serial positions 1 to 5 (all $p_B < .01$), whereas the intercepts of serial positions 1 to 5 could not be credibly differentiated from each other. For retro-cued probes, the intercept of serial position 6 was credibly smaller than the intercepts of serial positions 2 ($p_B = .02$), 3 ($p_B = .01$), and 4 ($p_B = .01$), but there was no such evidence in comparison to the intercepts of serial positions 1 ($p_B = .23$) and 5 ($p_B = .50$).

Positive trials - retro-cue benefit on intercept. We next investigated the effects of displaying a retro-cue during the retention interval. As mentioned before, we found no credible pairwise differences for the rate parameter, and we therefore focused on the intercept parameter. Aggregated across all serial positions we found a smaller intercept for retro-cued in comparison to non-cued probes ($p_B < .001$, 93.6 ms [57.6, 128.4]). Figure 6 shows the retro-cue benefits across serial positions. As can be seen, the 95% CIs do not include 0 for all but two serial positions, 2 and 6. However, even for those serial positions, the posterior median was very similar to the effects observed for serial positions 3 and 4. In addition, for

Table 1: Median group-level parameters for Experiment 1

	SP 1	SP 2	SP 3	SP 4	SP 5	SP 6
			Intercept			
δ_{NC}	$0.38^{ab}_{[0.32,0.43]}$	$0.38^{a}_{[0.34,0.42]}$	$0.37^{ab}_{[0.34,0.41]}$	$0.36^{ab}_{[0.32,0.40]}$	$0.32^{be}_{[0.29,0.36]}$	$0.22^{cd}_{[0.16,0.27]}$
δ_{RC}	$0.23^{cd}_{[0.14,0.31]}$	$0.31^{abce}_{[0.22,0.38]}$	$0.29^{ce}_{[0.23,0.35]}$	$0.29^{ce}_{[0.23,0.33]}$	$0.20^{cd}_{[0.12,0.27]}$	$0.16^{d}_{[0.07,0.24]}$
			Rate			
β_{NC}	$2.61^{a}_{[1.55,3.81]}$	$4.40^{a}_{[2.60,5.98]}$	$3.85^{a}_{[2.61,5.17]}$	$4.30^{a}_{[2.94,5.59]}$	$3.77^{a}_{[2.68,4.94]}$	$3.90^{a}_{[2.67,5.26]}$
βRC	$3.64^{a}_{[2.30,5.06]}$	$3.95^{a}_{[2.35,5.37]}$	$3.76^{a}_{[2.63,4.99]}$	$3.76^{a}_{[2.37,5.05]}$	$3.19^{a}_{[1.97,4.55]}$	$3.49^{a}_{[2.05,5.09]}$
			Asymptote			
λ_{NC}	$2.21^{abcd}_{[1.58,3.12]}$	$1.58^{a}_{[1.19,2.07]}$	$2.02^{ab}_{[1.57,2.61]}$	$2.35^{bc}_{[1.89,2.97]}$	$2.86^{cde}_{[2.26,3.65]}$	$3.01^{de}_{[2.51,3.75]}$
λ_{RC}	$1.89^{ab}_{[1.36,2.67]}$	$1.62^{a}_{[1.20,2.17]}$	$1.91^{ab}_{[1.52,2.40]}$	$2.12^{abc}_{[1.67,2.65]}$	$2.54^{bcde}_{[1.97,3.29]}$	$3.23^{e}_{[2.60,4.20]}$

Note. Values are based on positive probes (see Appendix A.1 for negative probes). We report the 95% credible intervals in square brackets. Columns separate different serial positions (SP). Non-cued and retro-cued probes are reported in separate rows and are denoted with subscripts NC and RC, respectively. Analogous to the Jeffrey terminology recommendations (Jeffreys, 1961), we speak of "credible" evidence for a difference between two conditions when $p_B < .05$. These credible pairwise differences between conditions are displayed using a compact-letter display (Graves, Piepho, Selzer, & Dorai-Raj, 2012) such that for each parameter, conditions that do not share a letter differ credibly from each other with (e.g., $p_B < .05$ for the comparison of δ_{NC} for SP1 with letters a and b compared to $\delta_{RC}$for SP1 with letters c and d).

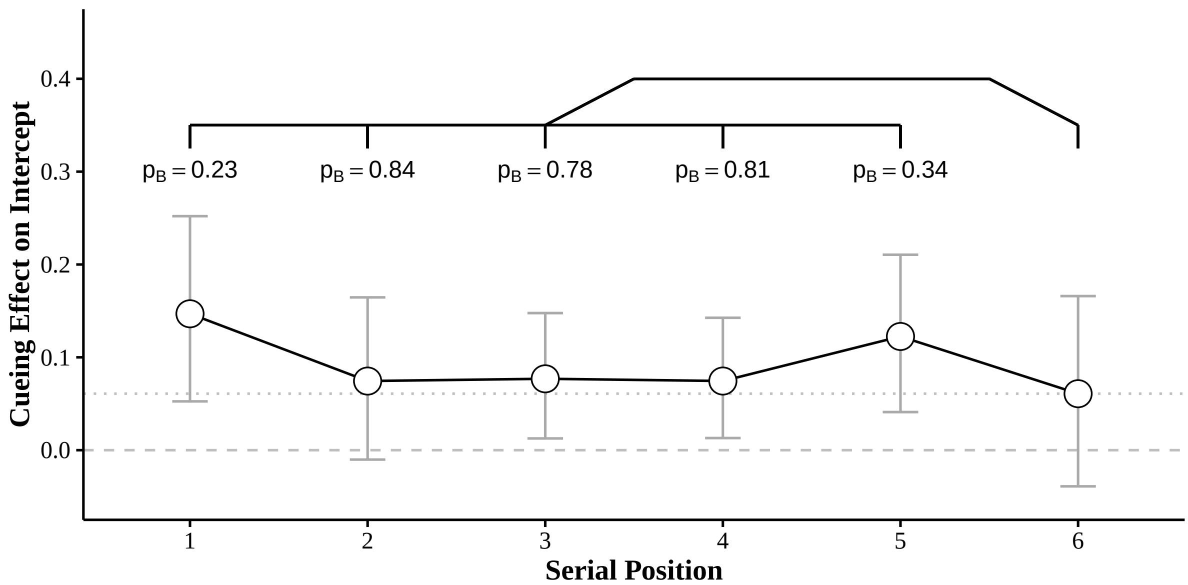


Figure 6: Median group-level posterior estimates for the retro-cue benefit in seconds for each serial position based on positive probes. p_B above serial positions 1 to 5 denotes the evidence for a difference of the cueing effect between this particular serial position and serial position 6. The dotted line depicts the median cueing effect for the last serial position. The dashed line indicates the absence of a cueing effect. Error bars depict 95% CI.

serial position 2, 96.5% and for serial position 6, 88.5% of the posterior mass was above zero.

The theoretically most important question is whether the retro-cue benefit is attenuated for the last item. To test this prediction, we compared the retro-cue benefit of serial position 6 against the mean retro-cue benefit of serial positions 1 to 5. This comparison provided no evidence for an attenuation of the retro-cue benefit ($p_B = .47$). We also compared the retro-cue benefit of serial position 6 with that of each earlier serial position individually. Figure 6 reports the p_B values for these comparisons and shows that none of these comparisons provides credible evidence for an attenuation of the retro-cue benefit (smallest $p_B = .23$). In other words, despite the fact that the retro-cue benefit appears to be slightly smaller for serial position 6, there is no evidence for this reduction when comparing the retro-cue benefits at different serial positions directly.

Positive trials - asymptote. We also investigated the effects of serial position and cue condition on the asymptote parameter of the SAT model. For both non-cued as well as retro-cued probes we found a higher asymptote for serial position 6 in comparison to serial positions 2 (both $p_B < .001$) and 3 (non-cued $p_B = .01$, retro-cued $p_B < .01$). In addition, for non-cued probes, the asymptote of serial position

5 was higher compared to serial position 2 ($p_B < .01$). For cued-trials, the asymptote of serial position 6 was also higher than serial position 1 ($p_B = .01$; i.e., there appeared to be a primacy effect for the non-cued items, but not for the cued items). Finally, we found no retro-cue benefits for the asymptote, neither when all non-cued probes were compared to all retro-cued probes ($p_B = .48$), nor when the non-cued and retro-cued conditions were compared for each serial position individually (all $p_B > .47$).

Bias and correlations. The median bias parameter was 0.26 [CI = 0.01, 0.52], indicating an overall bias to reject probes. We obtained no substantial correlation between individual-level parameters above .13, and all CIs included zero.

3.3.3. Discussion.

We merged the classical Sternberg task with the retro-cue paradigm in order to investigate whether the retro-cue benefit is attenuated for the last item. This prediction can be derived from the proposition that both phenomena are reflections of the same mechanism of a single-item focus of attention. We measured the full time course of retrieval using a response-deadline method. Analysis of the data using a hierarchical Bayesian implementation of the SAT function showed that the retro-cue benefit for the last item, which already benefits from being presented last, was not credibly smaller than the retro-cue benefit at other serial positions. This supports the claim that the retro-cue benefit is not attenuated for the last item. One potential criticism of the results of Experiment 1 is that the retro-cue benefit for the last item appears to be attenuated compared to the other items. However, a careful inspection of Figure 6 shows that even descriptively this is only the case in comparison to serial positions 1 and 5. In addition, an analysis of the posterior samples provides no evidence for this critique. Rather, the last-item benefit and the retro-cue benefit are additive effects of attentional prioritization in working memory.

A direct extension of the classical Sternberg task with the retro-cue paradigm as employed here results in two potential problems that limit the conclusions that can be drawn from this experiment. First, in this experiment we only used valid retro-cues. Thus, non-cued trials require the comparison of the probe stimuli to six other stimuli, whereas for retro-cued trials only one comparison is necessary. As a consequence, it remains a possibility that the retro-cue benefit could be solely driven by a reduction in the number of comparisons that need to be performed (Makovski et al., 2008). Second, because negative probes were not associated with a serial position (at least for non-cued trials) we could not calculate d' independently for each serial position. Consequently, we had to calculate SAT parameters separately for positive and negative probes, which led to a model with extra parameters that were not of direct relevance to the research question (i.e., the SAT parameters for the negative probes). In the classical SAT approach (McElree & Dosher, 1989), this problem does not occur because d' is calculated from the observed data before fitting the SAT function, recycling the negative probes for each serial position. As our Bayesian approach required us to specify the likelihood of the data (whereas the classical approach simply minimizes squared deviations) such a recycling would have been mathematically inappropriate.

In order to address these shortcomings of Experiment 1, in Experiment 2 and Experiment 3 probes were presented in one of the locations where items were presented in the study phase. The task required participants to compare the probe to the study item that had been presented in the probe's location. This ensures that only one comparison is required for non-cued and retro-cued probes, and further allows non-cued negative probes to be associated with the serial position of the probed location. This then allows us to estimate a single set of the SAT parameters for both negative and positive probes. With this procedure, we can more directly compare retro-cueing effects across serial position.

3.4. Experiment 2

In our second experiment, we modified the procedure of Experiment 1 only slightly by presenting location-specific probes. The participants' task was to indicate whether the probe and the item at the same location in the study array matched. In half of the trials, we presented a retro-cue that validly indicated the spatial location of where the probe will appear.

3.4.1. Method.

Participants. Eleven volunteers (8 females, mean age = 25), recruited through the University of Zurich participant volunteer pool, participated in ten test sessions each lasting 1h. 1-2 practice sessions were completed by each participant. Due to technical problems, data from one session of one participant was not recorded.

Material and design. We used the same materials as in Experiment 1, with the slight modification that we only selected five words per trial. In each session, participants completed 420 trials. In half of all trials we presented a positive probe, in a quarter of all trials a new probe which had not been part of the study set, and in the remaining quarter of trials we presented a probe that had been presented at a different serial position, a so called intrusion probe. Intrusion probes were equally likely to be chosen from all not-tested serial positions. Serial position, probe type, and response-deadline lag were permuted within each session and cue condition was varied across sessions. Five participants started with a session with retro-cues, and the remaining six started with a session without retro-cue presentation. This design yielded 30 positive trials for each combination of response-deadline lag, cue type, and serial position across the entire experiment. For negative trials, this design yielded 15 new and 15 intrusion probe trials for each experimental condition cell across the entire experiment.

Procedure. The same procedure was applied as in Experiment 1 with the following changes: Only five words were presented in five boxes that were presented equidistantly on a virtual circle. Also, for the deadline method, the number of lags was reduced to seven. Participants were cued to give an immediate response 100, 167, 300, 500, 767, 1100, or 1500 ms after probe onset.

3.4.2. Results.

Our main analyses will be restricted to positive and new negative probes. Analyses with intrusion probes can be found in Appendix A.2. The analysis of the intrusion probes supports the same conclusions regarding the interaction of serial position and cue condition. However, visual inspection of model fits suggests that SAT curves for intrusion probes require a more substantive theory regarding the underlying processes in order to capture the recognition performance dynamics during early processing times (Göthe & Oberauer, 2008; Oberauer, 2008). Here, we chose to fit the descriptive SAT model introduced by McElree (2006) in order to maintain comparability between experiments and analyses.

Response latencies. We excluded 2.11% of all trials due to extreme response latencies. We then investigated participants' response latencies to verify that participants obeyed the response-deadline instructions. After exclusion of extreme trials and averaged across participants and experimental conditions, the response-deadline criterion was met in 80.52 % of all trials. To account for different response latencies across experimental conditions, we again computed the processing time for each combination of participant, response-deadline lag, serial position and cue condition and used these times in the model based analysis.

Model-based analysis. After discarding 1,000 warmup samples, we retained 3,000 post-warmup samples for each of 4 independent chains. Convergence statistics indicated good mixing behavior with $\hat{R} \leq 1.01$ for all estimated model parameters (Gelman & Rubin, 1992). Visual inspection of MCMC trace plots of the group-level parameters indicated the same. The number of effective samples was above 800 for all estimated model parameters.

Model fits are depicted in Figure 7, which compares the median of the model predictions generated from the posterior distribution (the lines) to the observed proportions of "accept" responses (the dots), for positive and negative probes separately. Visual inspection of the model fit shows that the model accounted well for the retrieval dynamics of all experimental conditions. Median parameter values, 95% CIs, and results of all pairwise differences between experimental conditions are reported in Table 2.

Last-item benefit. As in Experiment 1, we found no credible differences between the experimental conditions for the rate parameter and thus focused on comparing conditions of the intercept parameter.

To test the last-item benefit, we compared the mean intercept for serial positions 1 to 4 with the mean intercept for serial position 5 across retro-cued and non-cued probes. This comparison revealed a credibly smaller intercept for serial position 5 ($p_B = .002$, 123.8 ms [52.1, 230.5]). We also observed this last-item benefit for non-cued probes ($p_B = .001$, 131.1 ms [67.3, 201.7]) and to a slightly lesser degree for retro-cued probes ($p_B = .05$, 116.7 ms [-1.5, 306.6]).

As shown in Table 2, we additionally investigated all pairwise comparisons for each combination of serial position and cue condition. For non-cued probes, the intercept for serial position 5 was smaller

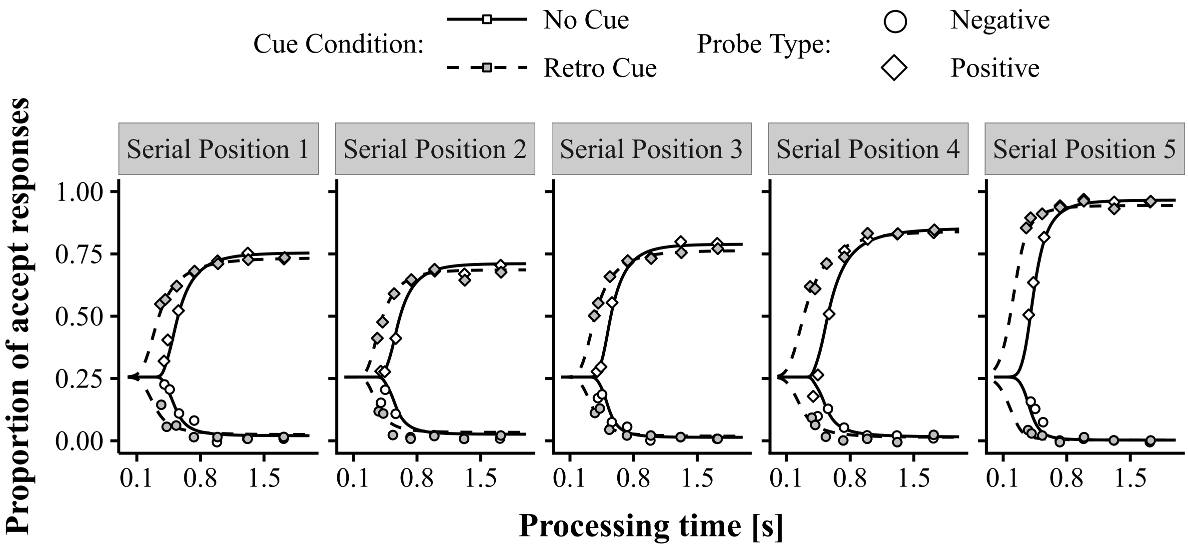


Figure 7: Observed (symbols) and predicted (lines) group-level proportion of accept responses for positive (diamonds) and negative (circles) probes for each serial position and cue condition as a function of processing times. Filled objects connected through a dashed line depict retro-cued probes whereas non-filled objects connected through a solid line depict non-cued trials.

than the intercepts of serial positions 1 to 4 (all $p_B < .01$), whereas the intercepts of serial positions 1 to 4 could not be credibly differentiated from each other. For retro-cued probes, the intercept of serial position 5 was smaller than the intercepts of serial positions 2 ($p_B = .006$) and 3 ($p_B = .02$), but there was no such evidence in comparison to the intercept of serial positions 1 ($p_B = .24$) and 4 ($p_B = .62$).

Retro-cue benefit. We next investigated the effects of presenting a retro-cue. Again, we focused on the intercept parameter, as we found no credible pairwise differences for the rate parameter. Aggregated across all serial positions, we found a smaller intercept for retro-cued in comparison to non-cued probes ($p_B < .001$, 223.9 ms [178.0, 285.0]). As can be seen in Figure 8, the retro-cue benefit was observed for each individual serial position.

To investigate whether the retro-cue benefit is attenuated for the serial position 5, we compared the magnitude of the retro-cue benefit of serial position 5 against the mean retro-cue benefit of serial positions 1 to 4. Again, this comparison yielded no evidence for an attenuation of the retro-cue benefit ($p_B = .84$). We also compared the retro-cue benefit of serial position 5 with each earlier serial position individually. Figure 8 reports the p_B values for these comparisons and demonstrates that none of these

Table 2: Median group-level parameters for Experiment 2

	SP 1	SP 2	SP 3	SP 4	SP 5
			Intercept		
δ_{NC}	$0.44^{a}_{[0.38,0.50]}$	$0.48^{a}_{[0.42,0.54]}$	$0.45^{a}_{[0.40,0.51]}$	$0.44^{a}_{[0.38,0.50]}$	$0.32^{d}_{[0.25,0.39]}$
δ_{RC}	$0.20^{bc}_{[0.08,0.28]}$	$0.30^{d}_{[0.22,0.37]}$	$0.27^{bd}_{[0.18,0.34]}$	$0.15^{c}_{[0.02,0.23]}$	$0.11^{c}_{[-0.08,0.22]}$
			Rate		
β_{NC}	$4.68^{a}_{[3.03,6.68]}$	$5.33^{a}_{[3.42,7.47]}$	$5.26^{a}_{[3.58,7.18]}$	$4.00^{a}_{[2.40,5.76]}$	$3.82^{a}_{[2.13,5.66]}$
βRC	$4.01^{a}_{[2.25,6.08]}$	$5.33^{a}_{[3.38,7.53]}$	$4.45^{a}_{[2.68,6.48]}$	$3.35^{a}_{[1.91,5.09]}$	$4.98^{a}_{[2.49,8.08]}$
			Asymptote		
λ_{NC}	$3.32^{ab}_{[2.39,4.33]}$	$2.81^{a}_{[2.03,3.67]}$	$3.40^{ab}_{[2.64,4.20]}$	$3.89^{bc}_{[2.92,4.86]}$	$5.87^{d}_{[4.60,7.28]}$
λ_{RC}	$3.11^{ab}_{[2.19,4.11]}$	$2.70^{a}_{[1.90,3.54]}$	$3.29^{ab}_{[2.48,4.13]}$	$3.76^{b}_{[2.89,4.67]}$	$5.22^{cd}_{[3.97,6.49]}$

Note. We report the 95% CIs in square brackets. Columns separate different serial positions (SP). Non-cued and retro-cued probes are reported in separate rows and are denoted with subscripts NC and RC respectively. Credible pairwise differences between conditions are displayed using a compact-letter display.

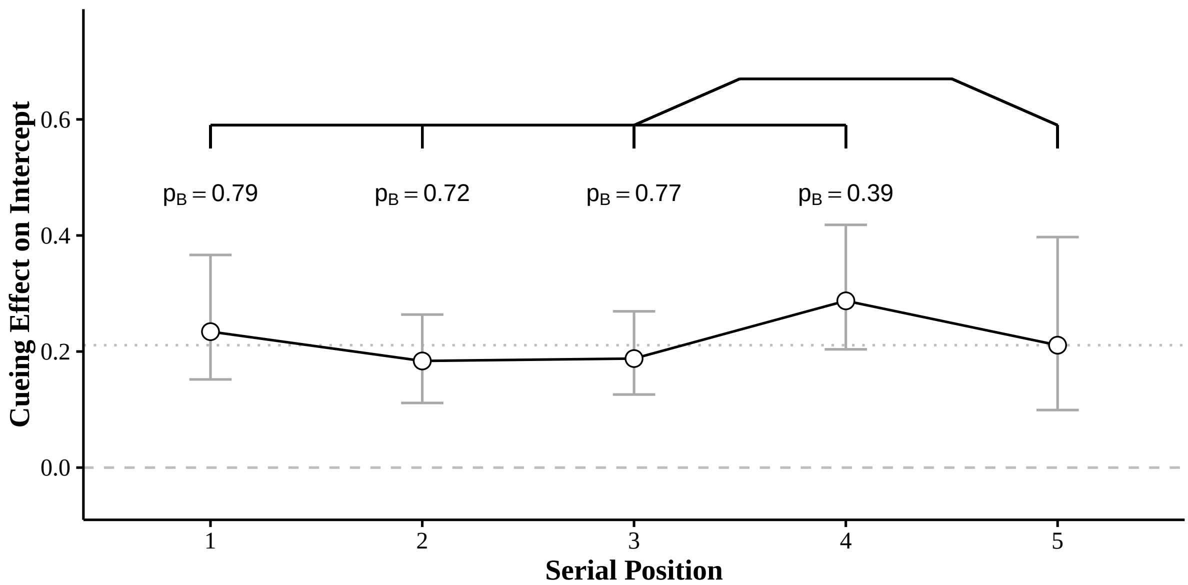


Figure 8: Median group-level posterior estimates for the retro-cue benefit in seconds for each serial position. p_B above serial positions 1-4 denotes the evidence for a difference of the cueing effect between this particular serial position and serial position 5. For serial positions 2 and 3, descriptively the cueing effect was smaller than for serial position 5 and p_B denotes the evidence for this direction. The dotted line depicts the median cueing effect for the last serial position. The dashed line indicates the absence of a cueing effect. Error bars depict 95% CI.

comparisons provides credible evidence for an attenuation of the retro-cue benefit (all $p_B > .39$). Descriptively the retro-cue benefit of serial position 5 was even larger than the retro-cue benefits of serial positions 2 and 3.

Asymptote. We also investigated the effects of serial position and cue condition on the asymptote parameter. For both non-cued as well as cued probes we found a higher asymptote for serial position 5 in comparison to all earlier serial positions (all $p_B < .05$). Moreover, for both cue conditions, the asymptote of serial position 4 was credibly higher than the asymptote of serial position 2 (non-cued $p_B = .02$, retro-cued $p_B = .01$). Finally, we found no retro-cue benefits, neither when all non-cued probes were compared to all retro-cued probes ($p_B = .25$), nor when the non-cued and retro-cued conditions were compared individually for each serial position (all $p_B > .20$).

Bias and correlations. The median bias parameter was 0.67 [CI= 0.44, 0.90] indicating an overall bias to reject probes. We obtained no substantial correlation between individual-level parameters above .14, and all CIs included zero.

3.4.3. Discussion.

Experiment 2 addressed two concerns of Experiment 1. By presenting probes at the same locations where they had been presented during the study phase, we were first able to associate non-cued probes to a serial position, and second, limit the number of comparisons to one for both non-cued and retro-cued probes. For non-cued probes, we again found a last-item benefit, as indicated by a faster intercept for the last item. Moreover, retro-cueing benefits on the intercept parameter were found for all serial positions with no attenuation for the last item, which already benefits from being the last item. This experiment thus provides additional evidence against the proposition that the mechanisms responsible for the last-item benefit are identical to the mechanisms that drive the retro-cue benefit.

Whereas the last-item benefit has predominantly been investigated using verbal material (McElree, 2006; McElree & Dosher, 1989) the retro-cue benefit is most often studied using visual material such as colors and orientations (Souza & Oberauer, 2016). In order to generalize our results to the focus of attention in visual working memory, Experiment 3 measured SAT functions for serially presented color patches with or without a retro-cue.

3.5. Experiment 3

In our third experiment, we replicated the procedure of Experiment 2 with colors instead of words as stimuli. Moreover, we addressed two experimental parameters that could possibly limit the generalization of our previous results. First, in Experiments 1 and 2, the last-presented item was always presented in the top left corner of the screen. Although we consider it as highly unlikely, the last-item benefit in these two experiments could be driven by a spatial preference of attention for items presented in the top left corner. Second, because no visual masks were used, after a retention interval of 500 ms some faint iconic traces could still be left that would support the last-item benefit without relying on attentional processes. To address these two issues, in Experiment 3, we varied the spatial position of the last item and extended the retention interval between the offset of the last item and the onset of the probe or the retro-cue.

3.5.1. Method.

Participants. Ten volunteers (9 females, mean age = 26) recruited through the University of Zurich participant volunteer pool participated in ten test sessions each lasting around 1h, after completion of a one-hour practice session.

Material and procedure. Color patches (diameter = 5.9°) were filled with one of nine distinct colors (RGB codes in brackets): Dark green (0,63,0), blue (0,0,255), green (0,255,0), yellow (255,255,0), pink (255,50,255), turquoise (90,160,255), orange (255,127,0), brown (127,45,0) and red (255,0,0).

Presentation of color patches occurred in serial order along the virtual circle in clock-wise direction starting at a randomly selected placeholder. The retention interval that spans from the offset of the last color patch until either the onset of a probe (in the no-cue condition), or the onset of a retro-cue (in the retro-cue condition), was set to 1000 ms. All other experimental parameters were identical to Experiment 2.

3.5.2. Results.

Analysis will be restricted to positive and new trials. We report all analyses with d' calculated by relating positive with intrusion probes in Appendix A.3. These analyses support the same conclusions regarding the interaction of serial position and cue condition. Visual inspection of intrusion trials suggests that a more complex model would have to be fitted in order to account for retrieval dynamics at early response-deadline lags.

Response Latencies. We excluded 2.08% of all trials due to extreme response latencies. After exclusion of these trials, the response-deadline criterion was met in 91.5 % of all trials, which indicates that participants obeyed to the response-deadline instructions. To account for different response latencies in the model-based analysis, we computed processing times for all combinations of participants, response-deadline lags, serial position and cue condition.

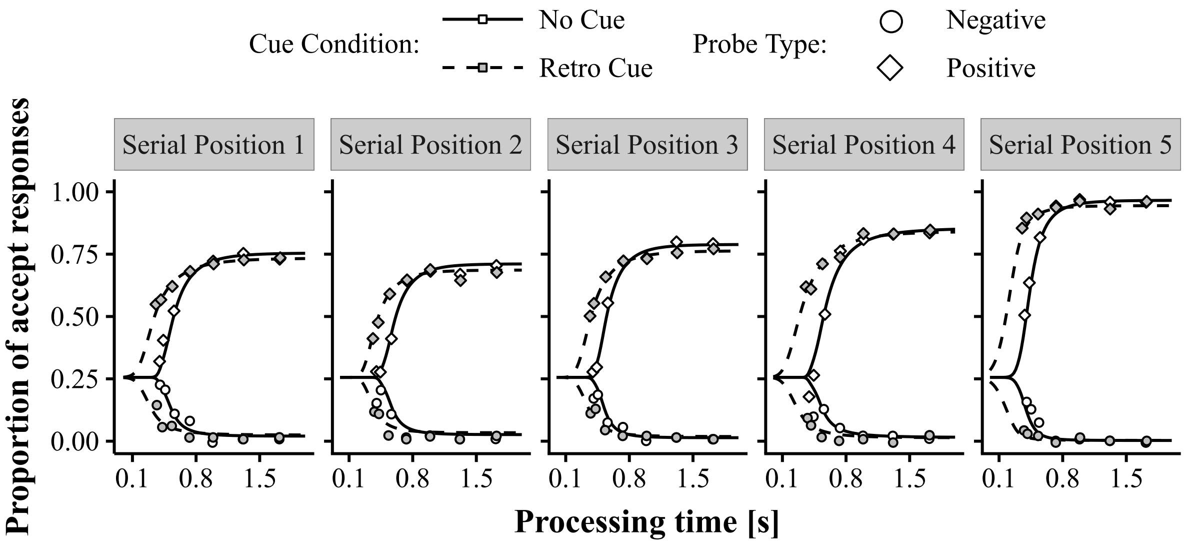


Figure 9: Observed (symbols) and predicted (lines) group-level proportion of accept responses for positive (diamonds) and negative (circles) probes for each serial position and cue condition as a function of processing times. Filled objects connected through a dashed line depict retro-cued probes whereas non-filled objects connected through a solid line depict non-cued probes.

Model-based analysis. We fitted the same model to the data as in Experiment 2. After discarding 1,000 warmup samples, keeping every fifth sample, we retained 3,000 post-warmup samples for each of 4 independent chains. Convergence statistics indicated good mixing behavior with $\hat{R} \leq 1.01$ for all estimated model parameters (Gelman & Rubin, 1992). Visual inspection of MCMC trace plots of the group-level parameters indicated the same. The number of effective samples was above 400 for all estimated model parameters. Model fits are depicted in Figure 9, which compares the median of the model predictions generated from the posterior distribution (the lines) to the observed proportions of "accept" responses (the dots), for positive and negative probes separately. Visual inspection of the model fit shows that whereas positive probes are well captured by the model, this is less the case for new probes. The observed pattern suggests that participants had a strong bias to reject probes, and accumulated evidence for accepting probes over time. Median parameter values and pairwise differences between experimental conditions of interest are reported in Table 3.

Last-item benefit. We found no credible differences of theoretical interest between the experimental conditions for the rate parameter, and thus focused on comparing the intercept parameter between

Table 3: Median group-level parameters for Experiment 3

	SP 1	SP 2	SP 3	SP 4	SP 5
			Intercept		
δ_{NC}	$0.45^{a}_{[0.39,0.52]}$	$0.42^{a[0.35,0.51]}$	$0.43^{a}_{[0.36,0.50]}$	$0.30^{c}_{[0.23,0.36]}$	$0.28^{c}_{[0.20,0.36]}$
δ_{RC}	$0.10^{b}_{[-0.16,0.21]}$	$0.02^{b}_{[-0.32,0.18]}$	$0.09^{b}_{[-0.20,0.22]}$	$-0.08^{b}_{[-0.59,0.12]}$	$-0.07^{b}_{[-0.64,0.14]}$
			Rate		
β_{NC}	$6.48^{a}_{[4.24,9.00]}$	$3.80^{b}_{[2.03,5.95]}$	$4.90^{ab}_{[2.89,7.11]}$	$4.63^{ab}_{[2.84,6.63]}$	$5.88^{ab}_{[3.48,8.67]}$
βRC	$4.15^{ab}_{[1.97,6.82]}$	$3.51^{ab}_{[1.58,6.09]}$	$4.34^{ab}_{[2.07,6.96]}$	$4.28^{ab}_{[2.11,6.98]}$	$5.35^{ab}_{[2.33,9.57]}$
			Asymptote		
λ_{NC}	$1.96^{a}_{[1.33,2.70]}$	$1.89^{ab}_{[1.19,2.68]}$	$1.99^{ab}_{[1.38,2.69]}$	$2.96^{c}_{[2.28,3.70]}$	$4.32^{d}_{[3.41,5.28]}$
λ_{RC}	$2.43^{bc}_{[1.76,3.20]}$	$2.04^{ab}_{[1.34,2.84]}$	$2.10^{ab}_{[1.47,2.80]}$	$2.91^{c}_{[2.25,3.65]}$	$4.26^{d}_{[3.41,5.20]}$

Note. We report the 95% CIs in square brackets. Columns separate different serial positions (SP). Non-cued and retro-cued probes are reported in separate rows and are denoted with subscripts NC and RC respectively. Credible pairwise differences between conditions are displayed using a compact-letter display.

conditions. To test the last-item benefit, we compared the mean intercept for serial positions 1 to 4 with the mean intercept for serial position 5 across cued and non-cued probes. This comparison revealed no credible difference ($p_B = .18$, 101.5 ms [-42.2, 402.5]). When we analyzed the last-item benefit for each cue condition separately, we did observe a last-item benefit for non-cued probes ($p_B = .007$, 119.9 ms [37.7, 211.3]), but not credibly for retro-cued probes ($p_B = .60$, 81.1 ms [-192.5, 670.4]). Although the posterior medians of both last-item benefits were of similar magnitude, the considerably larger CI of the latter one led to this result.

As shown in Table 3 we additionally investigated all pairwise comparisons for each combination of serial position and cue condition. For non-cued probes, the intercept for serial position 5 was smaller than the intercepts of serial positions 1 to 3 (all $p_B < .01$), but not in comparison to the intercept of serial position 4 ($p_B = .68$). The intercept for serial position 4 was credibly smaller than the intercepts for serial positions 1 to 3 (all $p_B < .002$). For retro-cued probes, the intercept of serial position 5 was not smaller than the intercepts of serial positions 1 to 4 (all $p_B > .32$).

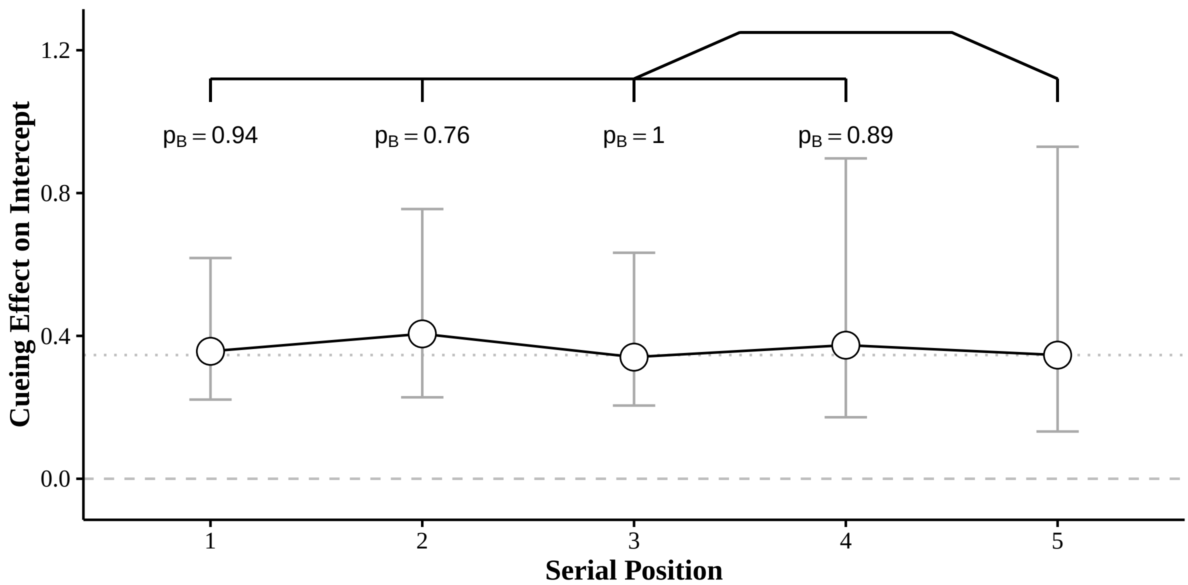


Figure 10: Median group-level posterior estimates for the retro-cue benefit in seconds for each serial position. p_B above serial positions 1-4 denotes the evidence for a difference of the cueing effect between this particular serial position and serial position 5. The dotted line depicts the median cueing effect for the last serial position. The dashed line indicates the absence of a cueing effect. Error bars depict 95% CI.

Retro-cue benefit. We next investigated the effects of presenting a retro-cue. Again, we focused on the intercept parameter as we found no credible pairwise differences of theoretical interest for the rate parameter. Aggregated across all serial positions, we found a smaller intercept for retro-cued in comparison to non-cued probes ($p_B < .001$, 386.0 ms [273.3, 563.3]). As can be seen in Figure 10, the retro-cue benefit was observed for each serial position individually.

To investigate whether the retro-cue benefit is attenuated for serial position 5, we compared the magnitude of the retro-cue benefit of serial position 5 against the mean retro-cue benefit of serial positions 1 to 4. Again, this comparison yielded no evidence for an attenuation of the retro-cue benefit ($p_B = .82$). We also found no evidence for attenuation when the mean retro-cue benefit of serial positions 4 and 5 was compared against the mean retro-cue benefit of serial positions 1 to 3 ($p_B = .99$). We also compared the retro-cue benefit of serial position 5 with each earlier serial position individually. Figure 10 reports the p_B values for these comparisons and demonstrates that none of these comparisons provides credible evidence for an attenuation of the retro-cue benefit (all $p_B > .76$).

Asymptote. We again also investigated the effects of serial position and cue condition on the asymptote parameter. For both non-cued as well as cued probes we found a higher asymptote for serial position 5 in comparison to all earlier serial positions (all $p_B < .007$). Moreover, for non-cued probes, serial position 4 also had a higher asymptote than earlier serial positions (all $p_B < .004$). For retro-cued trials, the asymptote of serial position 4 was higher than the asymptote of serial position 2 ($p_B = .008$) and 3 ($p_B = .003$), but not 1 ($p_B = .12$).

Finally, we compared the mean asymptote for all non-cued against all retro-cued probes. We found no evidence for a difference ($p_B = .85$). We also compared the non-cue against retro-cue condition for each serial position individually. We found a credible retro-cue benefit for serial position 1 ($p_B = .02$), yet we found no such evidence for serial positions 2 to 5 (all $p_B > .48$).

Bias and correlations. The median bias parameter was 0.46 [CI= 0.20, 0.70] indicating a trend towards rejecting the probe. Correlations among group-level parameters were generally low (<.14), and all CIs included zero.

3.5.3. Discussion.

The purpose of Experiment 3 was to determine whether the conclusions drawn from Experiment 2 can be extended to visual working memory, a lengthened retention interval, and spatially varying locations of the last item. The results indeed closely mirrored those obtained with verbal stimuli in Experiment 2. The crucial comparison of the magnitude of the retro-cue benefit across serial positions clearly shows that the retro-cue benefit was not attenuated for the last item.

One specific aspect of the results in Experiment 3 worth noting is that the last-item benefit on retrieval speed for non-cued probes was found to be extended to the second-to-last item. McElree and Dosher (1989) reported a similar finding, in which he showed that the retrieval speed benefit extended to three items when they could be semantically grouped with each other. However, here no grouping based on a semantic category was possible. Moreover, a quarter of all trials involved intrusion probes (e.g., a probe presented in the last item's position, but matching the next-to-last item). In order to correctly reject such probes, it would be fatal to group multiple items together in such a way that they are retrieved and compared to the probe together, rather than individually. We give a possible explanation of this finding when discussing the mechanisms of the last-item benefit in the General Discussion.

In comparison to Experiments 1 and 2, we did not observe a last-item benefit for retro-cued probes. This is likely due to a floor effect. The intercept of all retro-cued conditions was close to, or even below, zero, which left no room for effects of serial position to be detected. In addition, the precision of the parameter estimate for the last two serial positions was extremely poor compared to all other intercept estimates in this manuscript. This further diminished our chances of finding a last-item benefit here. The median posterior estimate of the last-item benefit for cued items was very close to that for non-cued items, supporting our contention that there is no real difference in the size of the last-item benefit between the two cueing conditions.

3.6. General Discussion

We set out to investigate whether the last-item benefit and the retro-cue benefit are driven by the same mechanism of a single-item focus of attention. We tested the prediction that, if both effects are driven by the same mechanism, the retro-cue benefit should be attenuated when the retro-cue is directed to the item which already benefits from being presented last. We presented items in serial order and assessed participants' memory with a central (Experiment 1) or location-specific (Experiments 2 and 3) recognition probe. While participants held studied items in working memory, in half of the trials we presented a retro-cue which indicated the item relevant for the subsequent comparison to the probe. To investigate retrieval speed, we measured SAT functions with the response-deadline method. Across three experiments, we found additive last-item benefits and retro-cue benefits on the SAT intercept, which allows us to conclude with confidence that the retro-cue benefit is not attenuated for the last item. Therefore, the retro-cue benefit and the last-item benefit are likely to be driven by different mechanisms.

Our results extend previous research providing indirect evidence for a dissociation between the prioritization of the last-item and the retro-cue benefit. Donkin and Nosofsky (2012a) proposed that the last-item benefit reflects the extreme point of a continuous but steep power gradient on memory strength, rather than a special status of the last item. Moreover, Hu et al. (2014) showed that presenting interfering visual material after the study list especially impaired performance for the last item, whereas retro-cued items are protected from different kinds of visual interference (Souza et al., 2016; van Moorselaar et al., 2014). Together, these findings provide converging evidence for a distinction between at least two forms of attentional prioritization: Attentional selection through retro-cues and the prioritization by virtue of the last serial position involve different mechanisms. A recent finding by Kalogeropoulou, Jagadeesh, Ohl, and Rolfs (2017) even indicates a potential third form of attentional prioritization. They orthogonally manipulated the validity of pre-cues and retro-cues in a delayed-estimation task of oriented gratings. They found no evidence for an attenuation of the retro-cue benefit when the retro-cued item had already been validly pre-cued. Therefore, attentional prioritization mechanisms involved in pre-cues may be differentiated from mechanisms involved in retro-cues as well.

3.6.1. Which parameter reflects the last-item and retro-cue benefit.

Across all three Experiments, we were able to replicate the last-item benefit reported by McElree and Dosher (1989), generalizing it to location-specific probes, and to visual materials. For non-cued items, the last item was shown to have a faster intercept parameter than any previous item, whose intercepts were found to be indistinguishable from each other. McElree and Dosher (1989) reported slightly better model performance when the last-item benefit was accounted for by a higher rate in comparison to a faster intercept parameter. In contrast, using more sophisticated modeling techniques, we here show that serial position effects on retrieval speed are best captured by the intercept parameter of the SAT function. Likewise, all observed retro-cue effects on retrieval speed were also consistently accounted for by the intercept, and not the rate parameter of the SAT function. In terms of the SAT function, these results imply that both the last-item benefit and the retro-cue benefit are driven by information being available sooner in time, rather than a faster accumulation of information once it is available. This notion has bearings for the following discussion of the potential mechanisms that drive these effects.

3.6.2. Mechanisms of retro-cue benefit.

Many hypotheses have been put forward to explain the retro-cue benefit (for a review, see Souza & Oberauer, 2016), including the propositions that retro-cues strengthen item-context bindings (Rerko & Oberauer, 2013), reduce interference from the test display (Makovski et al., 2008; Souza et al., 2014, 2016), and provide a head start of retrieval (Souza et al., 2016). Our results have implication for the plausibility of these explanations of the retro-cue benefit: Our finding that the retro-cue benefit reflects a shortened intercept parameter of the SAT function fits well with the head-start of retrieval hypothesis.

According to the head-start of retrieval hypothesis, retro-cues allow participants to start retrieving the retro-cued item ahead of the recognition decision-making period. As a consequence, when the probe appears, its comparison to the relevant item in memory can start sooner, and finish sooner. Shepherdson et al. (2017) fleshed this hypothesis out and proposed a two-stage model of short-term recognition: During the first stage, one item is retrieved from working memory, and in the second stage, that item is compared to the probe to arrive at a recognition decision. Support for this two-stage model came from an analysis of response-time distributions with the diffusion model (Ratcliff, 1978; Ratcliff & McKoon, 2008). Retro-cues were found to decrease the model's non-decision time parameter, which reflects the time that is required for non-decisional processes, including the time for retrieving an item from working memory. In addition, retro-cues increased the drift rate, which reflects the quality of information that enters the decision process. In line with the head-start of retrieval hypothesis, Shepherdson and colleagues argued that the retro-cue effect on the non-decision time parameter reflects the retrieval of an item into the focus of attention before the probe is presented (Ratcliff & McKoon, 2008; Sewell, Lilburn, & Smith, 2016). Our model-based analysis of the SAT curves converges with the analysis of response time distributions by Shepherdson et al. (2017): In SAT curves, the intercept reflects the duration of any process preceding the decision process, because during that time no evidence in favor of either response accrues. In contrast, the rate parameter reflects the rate at which evidence in favor of one or the other response accumulates over time. Therefore, the finding of a retro-cue benefit on the intercept confirms the conclusion of Shepherdson et al. (2017) that a retro-cue shortens the duration of a pre-decision process, arguably the retrieval of the relevant item from working memory.

Shepherdson et al. (2017) explained the retro-cue effect on drift rate as reflecting the protection of the cued item against interference by the probe, or other visual information at test (Makovski et al., 2008; Souza et al., 2016). Less interference implies that the comparison of the cued item to the probe provides better information, resulting in a higher rate of evidence accumulation towards the correct response, and as a consequence, faster and more accurate responses. Here we found no evidence that the retro-cue accelerated the rate of accumulation of evidence towards a response, and no evidence that it increased asymptotic accuracy. This renders protection from visual interference a less attractive explanation of the retro-cue benefit in our experiments.

The strengthening hypothesis states that a retro-cue strengthens the retro-cued item and the binding to its context (Rerko & Oberauer, 2013). Strengthened bindings improve access to representations, which is compatible with our findings of retro-cue benefits on retrieval speed. However, such strengthened bindings should also increase the quality of the information retrieved from working memory, and by implication, increase the rate of evidence accumulation, and improve performance at asymptotic levels. Yet, we found no evidence for retro-cue benefits on the rate or the asymptote parameter, which makes the strengthening hypothesis less plausible as an explanation of the retro-cue benefit.

The lack of a retro-cue benefit on asymptotic accuracy in our experiments contrasts with the common finding that retro-cue benefits improve accuracy (in addition to speed) in change-detection experiments (for a review, see Souza & Oberauer, 2016). It could be that in regular change-detection experiments, when there is no deadline and participants decide when to respond, participants choose to respond at a point in time where they have not reached their asymptotic level of evidence accumulation. Against this possibility, one experiment by Souza et al. (2016) found that forcing participants to delay their response by one second did not improve change-detection.

Retro-cues allowed participants to direct their eyes to the location of where the probe will appear, whereas in non-cued trials participants could do so only after probe onset. Although this could to some extent explain the retro-cue benefits in Experiments 2 and 3, it cannot explain the retro-cue benefit in Experiment 1, where probes were presented centrally and the eye could fixate the probe location ahead of time regardless of the retro-cue condition. Moreover, Griffin and Nobre (2003) showed in a task similar to ours that that retro-cue benefits are obtained even when participants' gaze is held in the center of the screen while probes are presented peripherally. Taken together, even though eye movements were not controlled in our experiments, we are confident that they play at best a minor role in explaining our results.

To conclude, our finding that, consistently across three experiments, the retro-cue only shortened the intercept parameter of the SAT function is best compatible with the assumption that the retro-cue enables a head start for retrieval of the relevant item, thereby shortening a processing stage preceding the decision stage.

3.6.3. Mechanisms of last-item benefit.

Can a head-start of retrieval mechanism also account for the last-item benefit? In line with such an explanation, McElree (2006) argues that the last-presented item does not have to be retrieved because it still is in the focus of attention. Therefore, the comparison of the probe to that item, which yields evidence towards one or the other decision, can commence immediately once the probe is presented. However, if indeed both the last-item benefit and retro-cue benefit arose from the fact that the relevant item is already in the focus of attention, we should have observed an attenuated retro-cue benefit for the last item: On this assumption, the last item is already in the focus of attention whether or not a retro-cue points to it, so there is nothing the retro-cue could contribute in addition. Our results rule out this scenario.

An alternative explanation of the last-item benefit is that it reflects the extreme point of a steep power gradient on memory strength (Donkin & Nosofsky, 2012a). Due to the rapid fall of strength, the last item seems to have a special status, when in fact memory strengths for these items simply reflect the power gradient. This proposition can well accommodate the finding of Experiment 3 in which we also found a faster intercept for the second-to-last item. If the slope of the power gradient is not as steep between the last two serial positions, the strength of the second-to-last item may still lie well in the non-asymptotic part of the power function.

The power law merely describes the pattern of memory strength with serial position. Possible causes for its pattern involve temporal distinctiveness and retro-active interference. According to a temporal distinctiveness account, retrieval of an item is driven by the uniqueness of its temporal context. The probability of successfully retrieving an item is a function of the distance from all other studied items along a temporal dimension. The last item can be distinguished easiest from all other memory items, because the retention interval following this item renders it more distinct (Brown et al., 2007). Moreover, the last item benefits from the absence of retro-active interference. All items but the last are interfered with by the presentation of subsequent memory items. The finding of Hu et al. (2014) that the recency effect on accuracy is diminished by a subsequent visual stimulus supports this notion.

3.6.4. Towards a mechanistic account of prioritization in working memory.

In an effort to go beyond the metaphoric use of the focus of attention, computational models have begun to describe the potential mechanisms involved in the selection of representations in working memory (e.g. Oberauer, 2013; Oberauer et al., 2013). We now outline how the last-item and retro-cue benefit could be computationally implemented in such a framework. Computational models of working memory typically assume two layers, one that represents the memory contents (words, color patches), and another layer that represents their contexts (serial or spatial position; Burgess & Hitch, 1999; Oberauer, 2013; Oberauer et al., 2012; Oberauer & Lin, 2017; Oberauer et al., 2013). Items are bound to their context by item-context bindings. Retrieval is initiated by activating the target item's context in the context layer. This activation is forwarded to the item layer through the item-context bindings. The stronger the activation of the target context, and the stronger the item-context binding, the higher a bound item is activated in the item-layer, which leads to a faster accumulation of evidence for the selection of this item.

We propose that the last-item benefit reflects a recency gradient on the activation of the context and on the strength of the item-context bindings, whereas a retro-cued item is actually retrieved, that is, the item representation is reactivated in the item layer. As a consequence, when the probe appears after a retro-cue, it can be compared to the memory representation immediately. Stronger item-context bindings imply not only faster retrieval but also better quality of the retrieved information, implying higher asymptotic accuracy, whereas a head start of the accumulation of evidence only implies that a particular asymptotic level is reached earlier. Our finding that the last-presented item has a higher asymptote than earlier items, whereas retro-cues do not affect the asymptotic performance, supports this proposition. Moreover, the strength of context activation or of item-context bindings is rapidly modifiable (Oberauer, 2013). In an effort to refresh earlier items, or to resurrect them from retroactive interference, context activation might shift to earlier list items. This can explain the finding that the last-item benefit rapidly diminishes over time (Donkin & Nosofsky, 2012b; Vergauwe & Langerock, 2017), or when instructions direct covert rehearsal to earlier list items (McElree, 2006).

This explanation also generates a novel empirical hypothesis: When a retro-cued item is retrieved, the context of the cued item - which acts as the retrieval cue for that item - must be activated. Therefore, the peak of context activation must be shifted from the last item to the retro-cued item. As a consequence, a retro-cue to an earlier list item should attenuate the last-item benefit. We would therefore expect that the magnitude of the last-item benefit is attenuated after a retro-cue has invalidly cued an earlier list item, and then the last list item is tested. (In our studies retro-cues were always valid and this prediction cannot be tested with the current data set.)

3.6.5. Multiple mechanisms of prioritization.

Additive benefits of the last list position and of retro-cues indicate that there are at least two forms of attentional prioritization of individual items in working memory. The last-item benefit reflects a recency gradient on the strength of item-context bindings, a process that occurs regardless of task demand. In contrast, the retro-cue benefit reflects the fact that the retro-cued item is retrieved, which is a selective and controlled process. This distinction is comparable to the difference between controlled and automatic mechanisms in working memory and perceptual attention. On the one hand, stored memory representations can be prioritized according to task demands in a selective, controlled manner. On the other hand, recency effects reflect an automatic updating process, which occurs regardless of task requirements (Rac-Lubashevsky & Kessler, 2016). The postulation of these multiple mechanisms of prioritization in working memory parallels the distinction of bottom-up and top-down mechanisms of prioritization in perceptual attention (Egeth & Yantis, 1997), although see a paper by Awh, Belopolsky, and Theeuwes (2012), arguing for a third category arising from the person's learning history. In a similar vein, the retro-cue may reflect "top down" attentional selection (i.e., driven by the person's goal and goal-relevant information from the cue), whereas the last-item benefit reflects a more "bottom-up" prioritization (i.e., to some extent independent of the person's goals, driven by the event sequence in the environment).

In summary, our proposition to distinguish controlled (retro-cues) and automatic (last-item) prioritization in working memory converges with a more global distinction between automatic and controlled processes of cognitive operations.

3.7. Conclusion

The present data provide evidence for two forms of attentional prioritization of single items in working memory. The retro-cue benefit reflects the operation of a goal-driven selection mechanism in working memory, which is the main function of the focus of attention. In contrast, the last-item benefit is a result of the unequal distribution of memory strength over list positions, resulting from the updating of working memory. Although this process imposes a prioritization gradient over items, it does not constitute a dedicated selection mechanism. Therefore, we propose to reserve the term focus of attention for the former but not the latter mechanism.

4. Vulnerability to Suffix Interference in Working Memory: Evidence for Two Distinct Forms of Prioritization

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Authors' contributions

MN Review of the literature, design of the research question, design of the study, programming with Matlab, data collection, data analysis and interpretation, writing of the manuscript.

KO Supervision and discussion of MN's contributions, revision of manuscript.

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4.1. Abstract

We examined whether items that are prioritized in working memory either by virtue of their last serial position in a list, or by means of retro- or pre-cues, are particularly susceptible to visual interference, or rather, are especially sheltered from interference. We sequentially presented four shape-color items for study and probed memory with a recall task. We varied the presentation of one or several visual suffix stimuli following the last list item, which participants were told to ignore. In half the trials we further indicated the item that was most likely to be probed using retro-cues (Experiment 4) or pre-cues (Experiments 5 to 7). We obtained evidence that the prioritized state of the last item comes with an increased vulnerability to visual interference. We show that the prioritized state of cued items does not render items more vulnerable to interference, but rather, the cue may be used to protect items from visual interference. These results provide evidence for a distinction of at least two distinct forms of prioritization in working memory. First, the last item, which renders items more vulnerable to visual interference, and second, cued items, which are protected from visual interference, and as such represent the focus of attention in working memory

4.2. Introduction

Working memory is a memory system that selects, maintains and manipulates information relevant for the current tasks (Cowan, 1999; Oberauer, 2002). Representations in working memory are not all maintained in an equal state of accessibility. The last item in a to-be-remembered list has been shown to be more accessible than previous items, arguably because it is held in a prioritized state (last-item benefit; McElree, 2006) . Moreover, representations maintained in working memory can be prioritized using cues (pre- and retro-cues; Griffin & Nobre, 2003; Souza & Oberauer, 2016). Here, we investigate whether these prioritized states render items more or less susceptible to suffix interference. A suffix is an irrelevant stimulus closely following the last list item.

Visual items in working memory that are prioritized through retro-cues have been shown to be protected from interference by new visual stimuli. In the retro-cue paradigm, a cue (typically a spatial cue) presented during the retention interval identifies the item that is most likely to be tested in a subsequently following memory task. An alternative way to guide prioritization in working memory is to indicate an item before presentation of study items (pre-cues; Griffin & Nobre, 2003; Nobre et al., 2004), which enables participants to prioritize the indicated item during encoding and retention. Cued items are reported faster and with higher accuracy (Griffin & Nobre, 2003; Landman et al., 2003; Souza & Oberauer, 2016). One proposed mechanism of the retro-cue benefit is that attention to an item in working memory protects that item from interference from subsequent detrimental visual input (Souza & Oberauer, 2016). Evidence for this proposition comes from studies showing that the cued item is protected from the visual interference introduced by masks (Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2014) and by the test display (Landman et al., 2003; Makovski et al., 2008; Pertzov et al., 2013; Shepherdson et al., 2017; Souza et al., 2016).

However, other research has suggested that items in a prioritized state in working memory are particularly vulnerable to interference. Studies have shown a disruption of memory performance by a suffix presented immediately after the offset of the study display (Ueno, Allen, et al., 2011; Ueno, Mate, et al., 2011). A recent study by Hu et al. (2014) extended the suffix paradigm by presenting the study items in sequential order, a procedure which is thought to leave the last item in a prioritized state (McElree, 2006). In some experiments they further introduced strategic incentives that either prioritized the first or the last list item. Performance for the prioritized item was increased. However, although participants were told that the suffix is redundant and can be ignored, its presentation impaired performance specifically for these prioritized items. These results led Hu et al. (2014) to postulate that the last item, as well as items strategically prioritized in response to incentives, reflect a common privileged state in working memory, which combines high accessibility with increased vulnerability (see also Manohar & Husain, 2016).

Theoretical models of working memory conceptualize prioritized items as being in a focus of attention (Cowan, 1998; Oberauer, 2002). In contrast to the view held by Hu et al. (2014), these models assume that representations in the focus of attention are stabilized and protected from interference. It is commonly believed that the focus of attention can be directed within working memory using retro-cues and pre-cues (Oberauer & Hein, 2012; Oberauer & Lin, 2017; Souza & Oberauer, 2016). The findings cited above, showing that retro-cued items are protected from visual interference, agree with the assumption of Cowan (1998) and Oberauer (2002) about the focus of attention, but stand in sharp contrast to the assumption of Hu et al. (2014) , and to their observation of heightened vulnerability of prioritized items to suffix effects. This contrast suggests that there are two different kinds of privileged states of items in working memory, one rendering the privileged item less vulnerable to interference from further visual inputs, and one rendering it more vulnerable.

A separate study from our lab provided additional reason to doubt that the retro-cue benefit reflects the same privileged state as the state of the last item. We have recently shown that the retro-cue benefit and the last-item benefit are additive, and therefore the last-item benefit and the retro-cue benefit are unlikely to reflect the same mechanism (Niklaus, Singmann, & Oberauer, 2017, see Study 1 of this thesis). We have argued that the retro-cue benefit reflects a goal-driven selection mechanism in working memory that is appropriately referred to as the focus of attention, whereas the last-item benefit does not reflect the focus of attention, but rather reflects an extreme point of a steep power-gradient on memory strength (Donkin & Nosofsky, 2012a). On the assumption that retro-cued items are not in the same state as the last item, we here assumed that retro-cued items are not exposed to the same increased vulnerability as the last item, and hypothesized that instead, retro-cued items are protected from suffix interference.

Taken together, research has shown that retro-cued items are protected from visual interference, whereas items prioritized by virtue of their last serial position, or strategic prioritization to match incentives, were especially vulnerable to a suffix. Here, we address this contrasting set of findings by extending the suffix procedure of Hu et al. (2014) with retro-cues and pre-cues to investigate which prioritized states in working memory are particularly susceptible to suffix interference, and whether retro- and pre-cues are used to protect the cued items from such interference.

4.3. Experiment 4

4.3.1. Method.

Participants. We recruited 26 volunteers (17 females, mean age = 25) through the University of Zurich participant volunteer pool, who participated in a 75 min test session. All participants read and signed an informed consent form before participation. Participation was reimbursed with 20 Swiss Francs.

Materials. The experiment was programmed and run in MATLAB using the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). All shown items were selected from a pool of 64 color-shape items formed by crossing eight saturated colors (red [RGB = 255,0,0], blue [0,0,255], yellow [255,204,0], green [0,255,0], sky blue [0,255,255], purple [153,0,153], gray [153,153,153], and black [0,0,0]) with eight shapes (circle, diamond, triangle, cross, arrow, star, flag, and arch). Suffixes were selected from the same pool as the study items, subject to the constraint that for each trial neither the color nor shape of the suffix was included among the four study items. The probe was either a color blob (not matching any of the eight shapes) corresponding to the color of one of the study items, or a black shape-outline corresponding to the shape of one of the study items. Sets of four study items were constructed by a random selection from the pool of 64 items. No shape or color was selected more than once per trial.

Procedure and design. Each trial began with the presentation of a fixation cross for 50 ms. Then, the numbers one through four were presented in the center of the screen with a presentation time of 250 ms and an inter-stimulus-interval of 250 ms. Participants were required to repeat the sequence "1-2-3-4" aloud at a speed of two numbers per second until the onset of the test probe. This concurrent-articulation procedure served to discourage verbal encoding of the memory items. The top row of Figure 11 depicts the flow of events in Experiment 4 after a 250 ms blank screen following the end of the concurrent-articulation procedure. Four color-shape items were presented one after another in the corners of an invisible square, with a presentation time of 250 ms and an inter-stimulus interval of 250 ms. The spatial presentation order was random. The center of the invisible square was 1.5°(degrees of visual angle at a viewing distance of approximately 50 cm) above the center of the screen, and the center-to-center distance between items was approximately 2.25°. After offset of the last item, and a 500 ms blank interval, we presented a retro-cue for 100 ms. The cue was either neutral and consisted of four arrows pointing to each corner of the invisible square, or it was a valid retro-cue which indicated with certainty the spatial location of the item that is going to be probed. After the offset of the cue, there was a 400 ms blank interval. Then, there either was a 750 ms blank screen in the no-suffix condition, or a suffix was presented for 250 ms in the suffix condition, followed by a 500 ms blank screen. Suffixes were presented at the center of the invisible square. In all conditions, a 250 ms auditory beep was played 400 ms after the offset of the cue. This beep was meant to help participants discriminate the to-be-ignored suffix from the study items. Finally, a test probe consisting of either a color blob or a shape outline appeared 1.5°below the center of the screen. When a color blob was presented, participants were required to recall the name of the shape associated with that color in the study sequence. When a shape outline was presented, they were required to recall the name of the color associated with that shape in the study sequence. We recorded participants' speech throughout the experiment.

The experiment consisted of a total of 288 trials divided into nine blocks. Each block resulted from a complete permutation of four probed serial positions, two dimensions (shape and color), two suffix types, and two cue conditions. Within each block, trials were presented in random order. Six practice trials were run before the experiment.

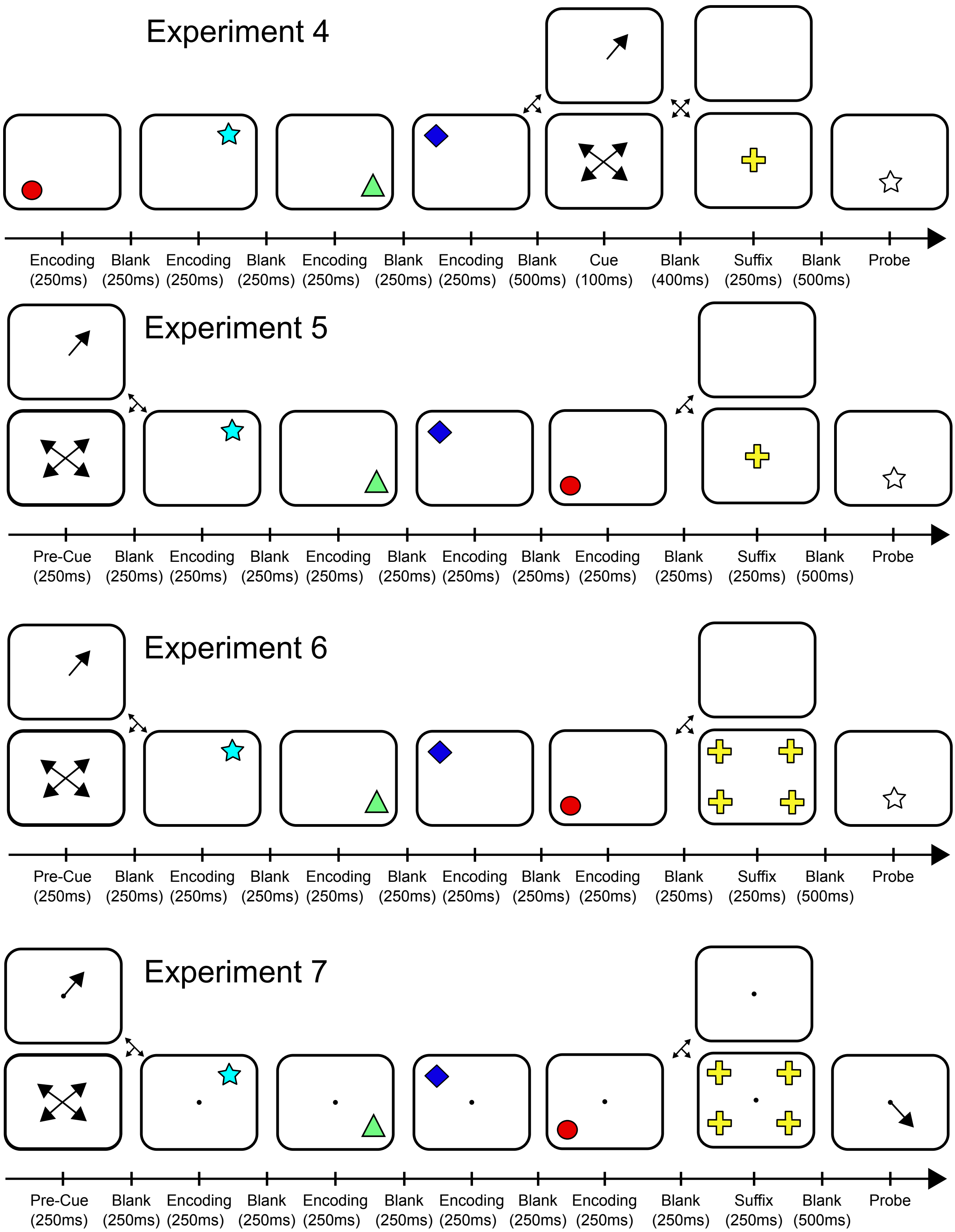
Experiment 4
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (500ms)
Cue (100ms)
Blank (400ms)
Suffix (250ms)
Blank (500ms)
Probe
Experiment 5
Pre-Cue (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Suffix (250ms)
Blank (500ms)
Probe
Experiment 6
Pre-Cue (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Suffix (250ms)
Blank (500ms)
Probe
Experiment 7
Pre-Cue (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Encoding (250ms)
Blank (250ms)
Suffix (250ms)
Blank (500ms)
Probe

Figure 11: Conceptual depiction of experimental procedures used in Experiments 4 (top row), 5(second row) 6 (third row) and 7 (bottom row). The shown flow of events is starting after a non-depicted 250 ms blank interval that follows the commencement of concurrent articulation. Experiments 4 through 6 show an example of a shape outline probe, which requires participants to recall the associated color (cyan). Experiment 7 shows an example of a spatial recall cue, which requires participants to recall the associated shape and color (green triangle) that was presented at this location. Cues are neutral (lower cue-squares),valid (upper cue-squares of Experiments 4-6) or invalid (upper cue-square in Experiment 7). Besides proportion correct, we were interested in specific types of errors. In the example of Experiment 4, recalling "red" is considered a within-sequence confusion, and recalling "yellow" is considered an intrusion. In the case where "yellow" was shown as a suffix color, this error is considered a suffix intrusion.

4.3.2. Data analysis.

We performed inferential analyses with the BayesFactor package (Morey, Rouder, & Jamil, 2015) for R (R Core Team, 2014). We compared a series of linear mixed models implemented with the $lmBF$ function. Hypotheses about predictors and their interactions were tested by including or omitting the effect in the fixed-effects structure of the models. We only considered models that met the constraint that if an interaction is included, the corresponding main effects were also included. Similarly, to test a three-way interaction, we used a model that included all lower-level two-way interactions and main effects. All considered models included the identical random effects structure which included a by-participant random intercept and by-participant random slopes for all predictors but the highest order interaction.

We report the main effects and interactions present in the best model, that is, the model with the highest Bayes factor in comparison to the baseline model that included no fixed effects ($BF_{Baseline}$). We further describe the best model in more detail by quantifying the evidence for including or omitting individual main effects and interactions. To this end, we assess the evidence for including an effect of interest (BF_{in}) by comparing the Bayes factor for the best model–including the effect–with the Bayes factor for the model excluding that effect. We also assess the evidence against an effect (BF_{out}) by comparing the best model – excluding that effect – to a model equivalent to the best model with the effect added. For example, let us assume compare a series of linear models with two predictors: A and B. In comparison to the baseline model, we find that the model with the highest Bayes factor ($BF_{Baseline}$ = 1000) includes both main effects of A and B. An alternative model that only includes an Effect of A and omits an effect of B has a $BF_{Baseline}$ of 100. The BF_{in} for an effect of B is the ratio of these two models: 1000/100 = 10. Moreover, the $BF_{Baseline}$ for the model that assumes an interaction in addition to the two main effects is 200. The BF_{out} against an interaction is 1000/200 = 5. The resulting Bayes factors provide the strength of evidence for or against an effect of a predictor on a continuous scale, with values further from 1 denoting increasingly strong evidence for one model over another. The above mentioned BF_{out} of 5 indicates that the data are 5 times more likely to be observed under a model that omits the interaction than under a model that includes the interaction. To assist the interpretation of Bayes factors, statisticians have proposed verbal labels for certain intervals on the BF continuum. Following Jeffreys (1961), we consider Bayes factors of less than 3 to only provide "anecdotal" evidence that are "not worth more than a bare mention". Bayes factors between 3-10, 10-30, 30-100 and $>$ 100 are denoted moderate, strong, very strong, and extreme evidence, respectively (Jeffreys, 1961) and adapted by Lee and Wagenmakers (2014).

To assess the difference between levels of a factor, we sampled 10,000 draws from the posterior distribution of the best model. The posterior distributions represent the probabilities of the parameters conditional on data and model, and thereby directly allow statistical inference (Gelman & Hill, 2007). We then simply subtracted the posterior distribution of the to-be-compared levels from each other to obtain a posterior distribution for their difference. For ease of interpretation, we always subtracted the distribution of the level with the smaller mean value from the distribution of the level with the larger mean larger value. In this way, between 0% and 50% of the posterior difference distribution lies below zero. The smaller the proportion below zero - or the larger the proportion above zero - the stronger the evidence for a difference between the two conditions. To gauge the strength of evidence for a difference, we calculated p_B as the proportion of the difference distribution below zero, multiplied by two. This makes p_B a statistic that ranges from zero to one, with values near zero denoting evidence for a difference, and values near one indicating that equal mass of the posterior difference distribution extended below and above zero. Values near one therefore provide some evidence against a difference.

4.3.3. Results and discussion.

We excluded 1.5% of all trials because the participant's oral response was not comprehensible, or the participant responded with a feature of the not-probed dimension. We collapsed the data over dimension (color or shape recall) because it is not a factor of theoretical interest.

Figure 12 depicts the mean proportion correct for each combination of cue type, suffix condition, and serial position. We first assessed whether the last list item benefits from its most recent serial position, while at the same time this prioritization renders it more vulnerable to suffix interference. To this end, we focused on neutral-cue trials. We compared a series of linear models with serial position (1 through 4) and suffix (presented or not presented) as predictors. Table 4 reports BF_{in} and BF_{out} of this analysis. We found extreme evidence for an effect of serial position. Assessment of posteriors for each serial position indicated that performance for the last item was better than for all earlier serial positions (all comparisons $p_B < .001$). We also found moderate evidence for an impairment of performance by a suffix. A theoretically important question is whether suffix costs differed across serial position (Hu et al., 2014). We found strong evidence against an interaction of suffix costs with serial position, contrary to the observation of Hu and colleagues (BF_{out} = 11.6). To test whether suffix costs are attenuated or increased for cued items, we considered both neutral and validly cued trials. We added several linear models to our series of model comparisons in order to account for the main effect and interactions of cue-type. As reported in Table 4, this analysis showed that, although retro-cues improved performance, there is moderate evidence that suffix costs were neither increased nor reduced for cued trials (BF_{out} = 4.3).

In summary, we observed that the presentation of a suffix impaired memory performance regardless of the probe's serial position or whether the probed item was retro-cued. We therefore failed to find evidence for the claims that suffix presentation especially impairs the last, or any prioritized item (Hu et al., 2016, 2014) , and likewise, we also found no evidence for the opposite claim that retro-cues protect items from visual interference (Makovski et al., 2008; Souza & Oberauer, 2016).

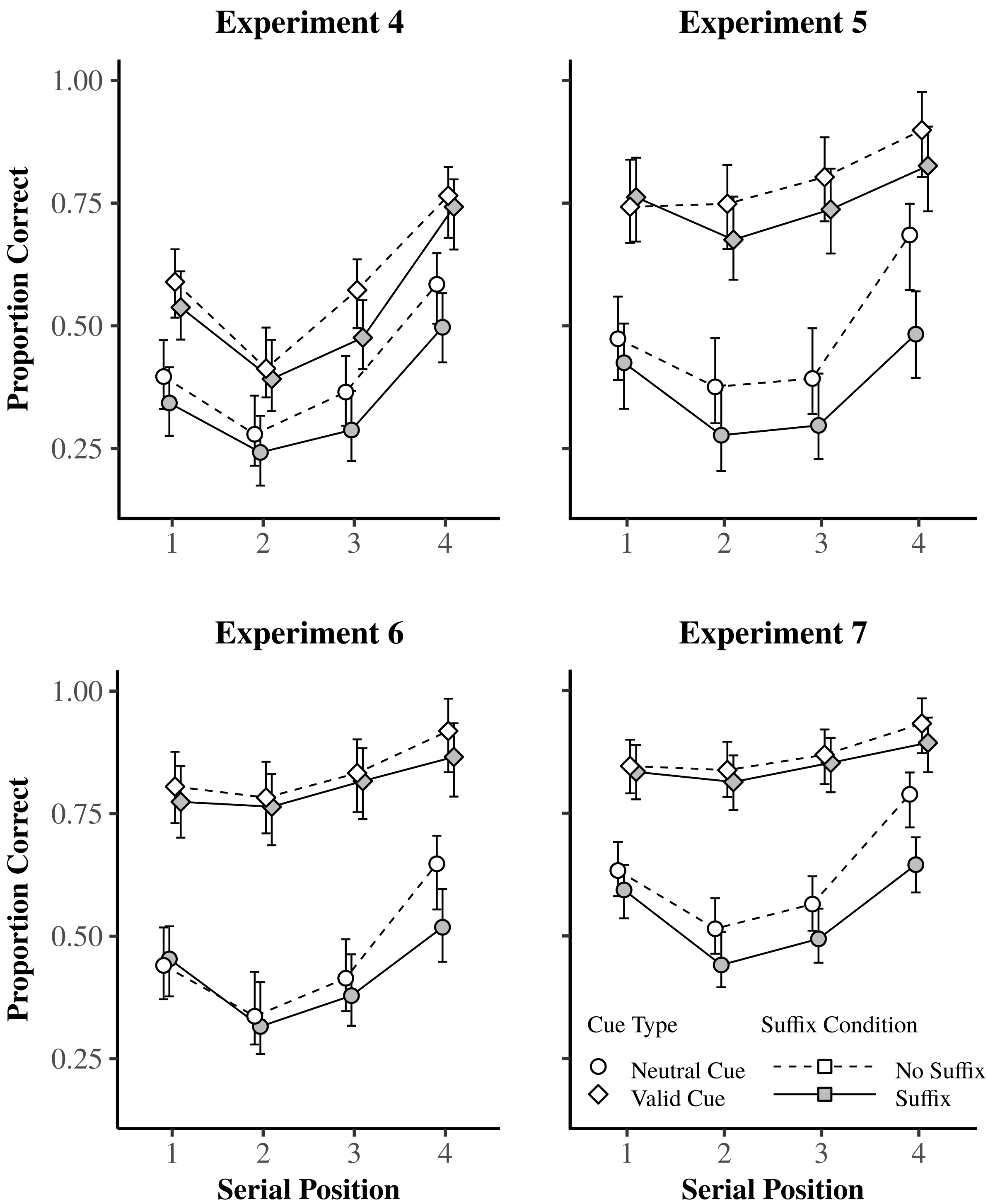

Figure 12: Mean proportion correct as a function of serial position, cue type and suffix condition for Experiments 4-7. Error bars denote the 95% highest density interval (HDI) based on 10'000 posterior samples of the full linear model which included all possible main effects and interactions (Kruschke, 2010; Morey et al., 2015)

Table 4: Bayesian analysis of proportion correct

Tested Effect	Experiment 1	Experiment 2	Experiment 3	Experiment 4
		Proportion Correct Neutral Cue Only Probes		
$BF_{Baseline}$	$2.2 * 10^{6}$	$2.1 * 10^{7}$	$3.8 * 10^{5}$	$6.5 * 10^{15}$
Sp	In > 1 million	In = 118,293.0	In = 589,067	In > 1 million
Suffix	In = 6.3	In = 308.0	Out = 1.5	In = 40,600
Sp: Suffix	Out = 11.6	In = 1.8	Out = 1.7	In = 4.1
		Proportion Correct Neutral and Validly Cued Probes		
$BF_{Baseline}$	$1.2 * 10^{19}$	$3.6 * 10^{17}$	$2.3 * 10^{16}$	$5.2 * 10^{34}$
Cue	In > 1 million	In > 1 million	In > 1 million	In > 1 million
Suffix	In = 90.5	In = 8,089.5	In = 1.8	In > 1 million
Sp	In > 1 million	In > 1 million	In > 1 million	In > 1 million
Cue : Suffix	Out = 4.3	In = 1.9	Out = 4.5	In = 28.1
Sp : Suffix	Out = 7.9	In = 2.8	Out = 2.1	In = 1.3
Sp : Cue	Out = 3.3	In = 11.5	In = 27.7	In > 1 million
Sp : Cue : Suffix	Out = 817.2	Out = 3.1	Out = 35.6	Out = 4.6

Note. Sp = Serial position. Interactions of predictors are denoted by a colon. $BF_{Baseline}$ denotes the Bayes factor of the best model versus a baseline model with no fixed effects. "In" and "Out" denote the Bayes factors for including (BF_{in}) the tested effect in the best model or for excluding it (BF_{out}), respectively.

4.4. Experiment 5

One noteworthy characteristic of our Experiment 4 is that the suffix was presented long after the offset of the last item. In order to rehearse or refresh memory representations (Baddeley et al., 1986; Barrouillet et al., 2007; Johnson, 1992; Souza et al., 2015; Vergauwe & Langerock, 2017), or to resurrect representations from retroactive interference (Oberauer et al., 2012), the focus of attention might have shifted away from the last item by the time the suffix appears (see Donkin & Nosofsky, 2012b; Vergauwe & Langerock, 2017). Our constant suffix costs across serial positions in the neutral-cue condition might therefore reflect a mixture of trials where the probed item was focused and impaired by the suffix, and trials where the probed item was not focused and therefore nor affected by a suffix.

In order to reduce the chance that the focus of attention has shifted away from the last item before the appearance of the suffix, in Experiment 5 we presented the suffix shortly after the offset of the last item. We externally guided prioritization with pre-cues instead of retro-cues. Pre-cues were not always valid to ensure that participants still had an incentive to encode all items in such pre-cued trials.

4.4.1. Method

We recruited 25 volunteers (22 females, mean age = 24). As depicted in the second row of Figure 11, we adapted the procedure in Experiment 5 as follows. 250 ms after offset of the last number presented for concurrent articulation, a pre-cue was presented for 250 ms, which indicated the spatial position of the item that is most likely to be probed. After a 250 ms blank screen, the four color-shape items were presented as in Experiment 4. After offset of the last stimuli, there was either a 1000 ms blank interval (no-Suffix condition) or a 250 ms blank screen, followed by a 250 ms suffix and a 500 ms blank screen. In all conditions, a 250 ms auditory beep was played 250 ms after the offset of the last item. The rest of the procedure was identical to Experiment 4.

The experiment consisted of a total of 266 trials divided into seven blocks. Each block resulted from a complete permutation of four probed serial positions, two dimensions of test, and two suffix conditions for neutral and validly cued probes. Therefore, there were as many neutral trials as validly pre-cued trials. In addition, in each block, we added 6 invalidly cued probes, which results in a cue validity of

72.7% (16 of 22 cued trials for each block were valid). Over the entire experiment, approximately the same number of invalid trials were shown for each combination of tested serial position, invalidly cued serial position, both suffix conditions, and both dimensions. Within each block, trials were presented in random order. Five practice trials were run before the experiment.

4.4.2. Results and discussion.

We excluded 0.81% of all trials because the participant's oral response was incomprehensible or the participant responded with a feature of the non-probed dimension. We again collapsed the data over dimension (color or shape).

As shown in Table 4 and Figure 12, proportion correct of neutral cue trials was higher for the last serial position than for all earlier serial positions (all comparisons of serial position 4 against other serial positions $p_B < .007$). We also found moderate evidence for an impairment of performance by a suffix, and there was anecdotal evidence that suffix costs differed across serial position. Analysis of posteriors showed that suffix costs were numerically larger at serial position 4 relative to serial position 1 ($p_B = .01$), serial position 2 ($p_B = .08$), and serial position 3 ($p_B = .07$).

Analysis of both neutral and validly cued probes provided extreme evidence that pre-cues improved performance. Moreover, we found anecdotal evidence that suffix costs were reduced for pre-cued trials ($BF_{in} = 1.9$).

In summary, Experiment 5 provided inconclusive results. We found only anecdotal evidence for the claim that the last item is especially vulnerable to suffix interference (Hu et al., 2014). Moreover, analyses provided only anecdotal evidence that pre-cued items are less vulnerable to suffix interference.

4.5. Experiment 6

To shed more revealing light on the ambiguous results obtained in the previous Experiment, in Experiment 6 we tried to move our suffix presentation procedure closer to conditions in which protection from visual interference for retro-cued items was observed in previous studies. Whereas in Experiments 4 and 5 we presented suffixes centrally, previous studies have shown that interference from visual stimuli is particularly strong when they spatially overlap with the memory items (Pinto et al., 2013), and retro-cues can protect from this interference (Pinto et al., 2013; Schneider et al., 2017; van Moorselaar et al., 2014) or from interference of the color in the color wheel spatially close to the probe (Souza et al., 2016). In Experiment 6 we thus presented suffixes that spatially overlapped with study items.

4.5.1. Methods.

We recruited 25 volunteers (17 females, mean age = 24). The same stimulus material and experimental design was used as in Experiment 5. As depicted in the third row of Figure 11, we adapted the procedure in Experiment 6 only as follows. Instead of a central suffix, we presented four suffixes at the locations where study items were presented. Within each trial, the shape-color combination of the suffix stimulus was the same for all four suffixes.

4.5.2. Results and Discussion.

We excluded 0.7% of all trials because the participant's oral response was incomprehensible or the participant responded with a feature of the non-probed dimension. We again collapsed the data over dimension. As shown in Table 4 and Figure 12, analysis of neutral cue trials indicated that performance for the last serial position was better than for all earlier serial positions (all comparisons of serial position 4 against other serial positions $p_B < .001$). Contrary to our expectation, we found anecdotal evidence against an effect of suffix. Moreover, there was anecdotal evidence against the notion that the suffix effect differs across serial position.

Analysis of both neutral and validly cued probes provided evidence that pre-cues improved performance. However, we found moderate evidence against the notion that suffix costs were affected by the cues. In summary, we observed ambiguous evidence on whether a suffix spatially overlapping the memory items affect performance. A study by Allen, Castellà, Ueno, Hitch, and Baddeley (2015) showed that the magnitude of suffix costs for spatially overlapping suffix stimuli is increased when participants have to use spatial information during retrieval. In light of their results, aiming to find clearer evidence for or against suffix costs, we required participants to use spatial information to recall items in Experiment 7. Moreover, as further explained below, the use of spatial retrieval cues during recall may also reveal protection from interference.

4.6. Experiment 7

Previous studies that have shown that retro-cued items are protected from visual interference (Makovski et al., 2008; Souza & Oberauer, 2016; van Moorselaar et al., 2014) identified the probed item with spatial cues. In models such as SOB-CS (Oberauer et al., 2012), or the network model of the phonological loop (Burgess & Hitch, 1999), retrieval is context-cue based. Stimuli are encoded by association to a context marker (such as its serial position, spatial location, or a feature), which can be used as a retrieval cue [10] to access the associated feature. The above mentioned studies presented items simultaneously, such that items were likely bound to the spatial location as this was the only relevant context available. Furthermore, this spatial context was required to access the probe. Among other things, a retro-cue strengthens the binding between the cued item and its (spatial) context (Rerko & Oberauer, 2013; Souza & Oberauer, 2016). This might protect the item-location binding from interference from additional visual stimuli presented in the same location. If that is the case, the protective effect of a retro-cue would be observed only when (1) the interfering visual stimuli are spatially close to or overlapping with the memory cue item, and (2) the item-location binding is used for retrieving that item, that is, the item is accessed through a spatial retrieval cue. In Experiment 7, we addressed this hypothesis by again presenting suffixes in the locations of memory items, and requiring participants to use spatial information in order to recall the tested item.

4.6.1. Methods.

We recruited 35 volunteers (26 females, mean age = 25). The same stimulus material and experimental design was used as in Experiment 6. As depicted in the bottom row of Figure 11, we adapted the procedure in Experiment 7 only as follows. Instead of probing participants with a single feature of an

[10] Retrieval cues must not be confused with retro- and pre-cues discussed so far. Retrieval cues, such as spatial location and serial position, are used to access and retrieve working memory representations that they are associated with.

object, we identified the tested object by a spatial probe, and participants were required to recall both features of that object. Moreover, a central dot was presented throughout the trial.

4.6.2. Results and discussion.

We excluded 0.7% of all trials because the participant's oral response was incomprehensible or the participant responded with a feature of the non-probed dimension. Our dependent variable was the mean of the proportion of correctly recalled features per trial (i.e. 0, 0.5, or 1).

As shown in Table 4 and Figure 12, analysis of neutral-cue trials indicated that performance for the last serial position was better than for all earlier serial positions (all comparisons of serial position 4 against other serial positions $p_B < .001$). We found very strong evidence for an effect of suffix, and there was moderate evidence that this effect differed across serial position. Analysis of posteriors suggested that suffix costs were numerically larger at serial position 4 relative to serial position 1 ($p_B = .003$), serial position 2 ($p_B = .04$), and serial position 3 ($p_B = .03$).

Analysis of both neutral and validly cued trials showed that cues improved performance. Crucially, we found strong evidence that suffix costs were reduced when a pre-cue was presented ($BF_{in} = 28.1$). Moreover, we compared an additional series of linear models including effects of cue type and suffix condition only for trials in which the last item was probed. The best model included both main effects of cue and suffix, as well as their interaction ($BF_{Baseline} = 1.8 * 10^{14}$). There was extreme evidence in support of the interaction ($BF_{in} = 1500.1$). Analysis of posteriors showed that suffix costs at serial position 4 were reduced for pre-cued (median costs = 0.04, [95% highest density interval = 0.00 - 0.08] relative to neutral cue probes (0.14, [0.10 - 0.18], $p_B < .001$).

In summary, there was moderate evidence that the last item is more susceptible to suffix interference than previous serial positions. Crucially, we found strong evidence that spatial pre-cues can be used to protect items, including the last item, from spatially overlapping, interfering stimuli. Therefore, this experiment provides evidence for the notion that there are at least two different kinds of privileged states of items in working memory, the cued item, which is protected from visual interference, and the last list item, which is rendered more vulnerable.

4.7. Error-Type Analyses

Our method provided valuable error information that allowed us to investigate the nature of the disruptive suffix effect, as well as the protection mechanisms from such visual interference. After exclusion of answers that did not include any of the 16 potential recall candidates in this series of experiment, two main types of errors can be differentiated (see also Figure 11). First, a within-sequence confusion denotes the erroneous recall of a feature from one of the three not-probed study items. Second, an intrusion denotes the erroneous recall of any of the four features (per dimension), that were not shown in the study list, including the feature of the suffix. The mean proportions of within-sequence confusions and intrusions are depicted in Figure 13. For both types of errors, we compared several linear mixed models including or omitting main effects and interactions of serial position, suffix, and cue type.

Within-sequence confusions. As reported in Table 5, across all four experiments, we obtained extreme evidence that there were more sequence confusions for neutral relative to validly cued probes, and that the proportion differed across serial position. Crucially, across all experiments we obtained moderate evidence against an effect of suffix on sequence confusions.

Intrusions. As reported in Table 5, we obtained extreme (E4 and E7), strong (E6) and moderate (E5) evidence that the presentation of a suffix increased the number of intrusions. Moreover, valid cues reduced the proportion of intrusions, and the proportion of intrusions differed across serial position. In the first three experiments, analyses yielded ambiguous evidence that cues affected suffix costs. Crucially, for Experiment 8, where the analysis of proportion correct showed that suffix costs were reduced with valid cues, there was strong evidence that the suffix effect on proportion of intrusions was reduced for valid relative to neutral cues.

Intrusion errors in the suffix condition can be divided into recalling either (a) a feature of the suffix or (b) any of the other three non-studied features. If all four non-studied features were equally probable to intrude, the percentage of a suffix intrusion given any intrusion should be 25%. Overall, we found that 44.5% (E1), 40.9% (E2), 40.7% (E3) and 45.3% (E4) of all intrusions in the suffix condition included a feature of the suffix. Bayesian t-tests (Morey et al., 2015) of percentages of suffix intrusions against

Table 5: Bayesian analysis of errors

Tested Effect	Experiment 1	Experiment 2	Experiment 3	Experiment 4
		Sequence Confusions		
$BF_{Baseline}$	$1.2 * 10^{11}$	$4.5 * 10^{11}$	$6.1 * 10^{11}$	$2.8 * 10^{25}$
Cue	In = 2,918.8	In = 45,132.1	In > 1 million	In > 1 million
Suffix	Out = 5.4	Out = 2.3	Out = 6.5	Out = 2.2
Sp	In > 1 million	In > 1 million	In = 100,664.1	In > 1 million
Cue : Suffix	Out = 16.4	Out = 8.9	Out = 18.6	Out = 6.6
Sp : Suffix	Out = 51.7	Out = 5.6	Out = 33.5	Out = 10.1
Sp: Cue	Out = 1.8	Out = 3.2	In = 1.2	In = 49,735.9
Sp:Cue:Suffix	Out = 4,275.2	Out = 479.4	Out = 361.7	Out = 488.5
		Intrusions		
$BF_{Baseline}$	$1.8 * 10^{14}$	$3.9 * 10^{6}$	$9.4 * 10^{9}$	$8.0 * 10^{19}$
Cue	In > 1 million	In = 93,724.6	In > 1 million	In > 1 million
Suffix	In = 643.1	In = 4.4	In = 18.7	In = 26,572.2
SP	In = 118,894.3	In = 43.4	In = 86.5	In > 1 million
Cue : Suffix	In = 1.2	In = 1.6	In = 1.0	In = 19.9
Sp : Suffix	Out = 7.8	Out = 2.2	Out = 8.4	Out =1.7
Sp: Cue	Out = 17.3	In = 2.7	Out = 3.3	In = 7.4
Sp:Cue:Suffix	Out = 1249.2	Out = 7.5	Out = 439.8	Out = 8.1

Note. Sp = Serial position. Interactions of predictors are denoted by a colon. $BF_{Baseline}$ denotes the Bayes factor of the best model versus a baseline model with no fixed effects. "In" and "Out" denote the Bayes factors for including (BF_{in}) the tested effect in the best model or for excluding it (BF_{out}), respectively.

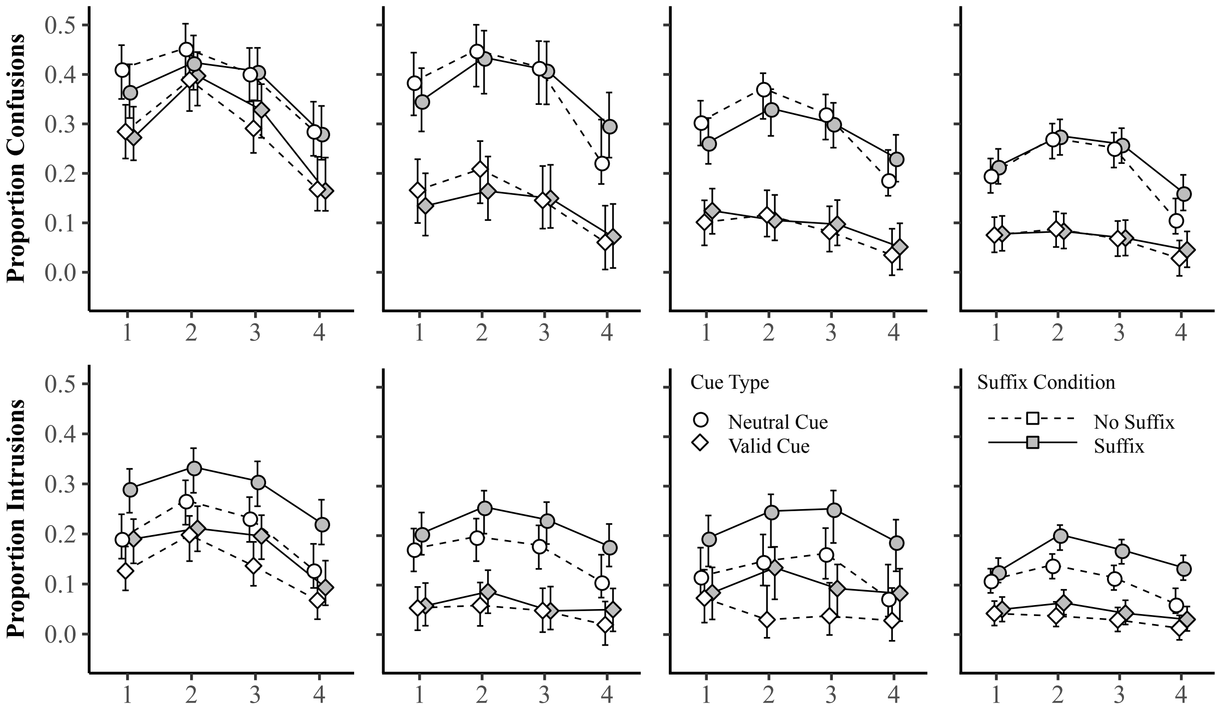

Figure 13: Top row: mean proportion of recalling a non-probed feature of the study list, denoted a within-sequence confusion. Bottom Row: Mean proportion of recalling a feature that was not part of the study list, denoted an intrusion error. Error bars denote the 95% HDIs based on 10'000 posterior samples of the full linear model which included all possible main effects and interactions (Kruschke, 2010; Morey et al., 2015)

25% yielded very strong to extreme evidence that suffix features were more likely to intrude than any other feature that was not present in the study list ($BF_{E1} = 949'147.3$,$BF_{E2} = 81.3$, $BF_{E3} = 3625.6$, and $BF_{E4} > 1\ million$).

In sum, the analysis of errors showed that suffix costs were driven by an increase of intrusions, which most often included a feature of the suffix. When cues can be used to reduce suffix costs (Experiment 7), they do so by reducing this increased number of intrusions for trials that included a suffix.

4.8. Pooled Proportion Correct Analysis Experiments 4-7

When no further incentives are given, the last item, which arguably is left in a prioritized state, has been shown to be more vulnerable to the presentation of a suffix (Hu et al., 2016, 2014). Across all four experiments, we found strong (E4) and anecdotal (E7) evidence against, and moderate (E7) and anecdotal (E5) evidence for this notion. Numerically, suffix costs were in fact larger for the last serial position in the neutral-cue conditions of all our experiments. To follow up on this pattern, we additionally tested whether credibly higher suffix costs for the last list item emerge when we considered the data from all four experiments simultaneously. To this end, we pooled the proportion-correct data of the neutral-cue trials across all four experiments. The compared models included main effects and interactions of serial position (1 through 4), suffix (presented or not presented) and an experiment identifier. The best model ($BF_{Baseline} = 4.3 * 10^{53}$) included main effects of serial position, suffix, experiment, and indeed an interaction of serial position with suffix. The crucial notion that suffix costs differed across serial position was supported by extreme evidence ($BF_{in} = 579.2$). Analysis of posterior samples indicated that suffix costs differed neither between serial positions 1 and 2 ($p_B = .28$) nor between serial positions 2 and 3 ($p_B = .64$), but that suffix costs at serial position 4 were credibly larger than at serial position 1 ($p_B < .001$), serial position 2 ($p_B < .001$), and serial position 3 ($p_B = .003$).

4.9. General Discussion

We set out to investigate whether items held in prioritized states in working memory are particularly susceptible to suffix interference, and whether items prioritized by means of retro- and pre-cues are also more susceptible to such interference, or rather, are protected from it. To this end, we combined the suffix procedure with the retro- and pre-cue paradigm. We observed three key results. First, across experiments, we found evidence that the last item was recalled best, and that this advantage came with an increased susceptibility to visual suffix interference. Second, we showed that retro- and pre-cues did not render items more susceptible to such interference. Finally, in line with previous research (Souza et al., 2016; van Moorselaar et al., 2014), when the to-be-recalled item was identified by a spatial probe, suffix costs were credibly reduced by a pre-cue.

All of these key patterns can be observed within Experiment 7. In the neutral-cue condition, when no further guidance for prioritizing one or another item is given, the last item was shown to be recalled best. This advantage came with an increased susceptibility to suffix interference. This supports the claim by Hu et al. (2014) that prioritized items in working memory are more vulnerable to suffix interference. However, we also showed that items that have been validly pre-cued are protected from such suffix interference, including the last item. This finding demonstrates that not all prioritized items in working memory are especially susceptible to suffix interference (Hu et al., 2016, 2014). We conclude that the last-item benefit and the retro-cue benefit reflect different privileged states. Niklaus, Singmann, and Oberauer (2017) proposed that the retro-cue benefit reflects the focus of attention in working memory, whereas the last-item benefit does not. In the present series of experiments we showed that pre-cued items are protected from interference. This supports the notion that cued items represent the focus of attention, because items selected by the focus of attention are thought to be protected from interference (Cowan, 1998; Oberauer, 2002). Accordingly, the increased vulnerability of the last item supports the claim that the last item does not reflect the focus of attention in working memory (Cowan, 2011; Niklaus, Singmann, & Oberauer, 2017). Similarly, Hu et al. (2014) reported increased susceptibility to suffix interference for items that were prioritized by means of strategic incentives. A critical difference between pre- or retro-cues, and such incentives is that the latter do not carry any predictive value regarding which item will be probed. In light of their results, we propose that the prioritized state of a highly-incentivized item does not reflect the focus of attention either.

4.9.1. Increased susceptibility of the last-item.

Hu et al. (2016, 2014) showed that the increased performance for the last item comes with an increased susceptibility to suffix interference. Although we found support for this proposition when we pooled the analysis across all four experiments, we obtained evidence both for and against this notion when we analyzed experiments individually. It appears that this interaction of suffix and serial position might be more fickle than previously reported.

A potential explanation for the variability across experiments is that in network models of serial-order memory (Burgess & Hitch, 1999; Oberauer et al., 2012), the suffix stimulus would naturally be encoded by association to a context marker for serial position 5 (in addition to being simultaneously associated with other contexts, such as its spatial location). In these models, context markers for neighboring positions are similar to each other. Therefore, when serial position is used as a retrieval cue to access a tested item, stimuli bound to neighboring serial positions will also be cued. To the extent that people use serial position as a retrieval cue to do the task, one should expect suffix costs to increase towards the recency part of the list, as reported by Hu et al. (2014). This is so because the context marker for serial position 4 overlaps closely with the context marker for serial position 5, and as a result the suffix is retrieved most often when the last serial position serves as retrieval cue. However, this increase of suffix costs over serial positions is predicted only if participants choose to retrieve a feature by use of a serial-position retrieval cue. Although people could use serial position as a retrieval cue, they don't have to. For instance, when given a color probe, they could (a) use the color to retrieve its serial position, and then use the serial position to retrieve the shape bound to it, (b) use the spatial position instead of the serial position as a mediator (Schneegans & Bays, 2017), or (c) use the color to directly retrieve the shape bound to it (also see Oberauer & Lin, 2017). Only mechanism (a) would be impaired by the association of a suffix with the last serial position.

We speculate that the difference between experiments may be because participants in different experiments have a preference for different retrieval strategies. Participants in our first three experiments may have preferably recalled items by use of a direct color-shape binding, or in our last experiment, by use of a spatial retrieval cue. The ambiguous or moderate evidence for the increased vulnerability of the last item observed in our experiments may reflect the fact that only in a small proportion of trials participants used serial position as a retrieval cue. Future studies could incentivize the use of serial position as a retrieval cue. According to our reasoning, this should lead to increased suffix costs for the last item.

Note that the proposition that participants did not consistently use serial position to recall the probe's other feature is not incompatible with the finding of serial position effects. Effects of serial position may be due to differences in memory strength. Donkin and Nosofsky (2012a) proposed that memory strength decreases with lag of serial position according to a power function. Thus, even when participants do not use serial position as a retrieval cue, the strength of the retrieved memory item varies systematically with serial position.

4.9.2. Mechanisms of suffix costs.

Across all experiments we observed the same two patterns of errors as reported by previous suffix studies (Hu et al., 2014; Ueno, Allen, et al., 2011). First, within-sequence confusions were not affected by the presentation of a suffix. This indicates that suffix costs are not driven by a weakening of color-shape bindings, because this should have led to more sequence confusions due to an increase in erroneous color-shape bindings. Second, suffix costs were instead driven by an increase of intrusions, which more often than chance involved a suffix feature.

This observed pattern of errors supports the proposition that the suffix is kept out of working memory by a perceptual attention mechanism that selects stimuli based on multiple dimensions, including their visual features, as well as their serial position, spatial position, and the concurrent tone we used to mark the suffix. Filtering consists of using these dimensions to determine whether to select or de-select a stimulus for encoding (Heinke, Backhaus, Sun, & Humphreys, 2007; Treisman, 1988; Ueno, Allen, et al., 2011; Ueno, Mate, et al., 2011; Vogel, McCollough, & Machizawa, 2005). Because the suffix has features from the pool of potential memory items, the suffix has a non-negligible probability of being encoded into working memory, and as a consequence tends to be confused with the tested memory item (Baddeley, Allen, & Hitch, 2011; Hu et al., 2014; Ueno, Allen, et al., 2011; Ueno, Mate, et al., 2011).

These filtering mechanisms provide a potential partial explanation of our findings in Experiment 6. We propose that in our experiments the perceptual attention mechanism was tuned to select single items for encoding. When it was faced with a four-suffixes array, it may have been able to use the difference on the numerosity dimension (4 vs. 1 stimuli) to more effectively close the gate into WM than in the other experiments. Such improved filtering of suffixes could explain why we did not find credible suffix costs in Experiment 6.

In summary, the pattern of errors indicates suffix costs are driven by an occasional failure of a perceptual attention mechanism whose function it is to keep suffixes from entering working memory. If suffixes make it past the filter, they tend to be confused with information maintained in working memory.

4.10. Conclusion

We challenge the generality of the proposition that items in the focus of attention are more vulnerable to suffix interference (Hu et al., 2014). We propose that there are at least two distinct forms of prioritization in working memory. On the one hand, items prioritized by virtue of their last serial position are more vulnerable to irrelevant visual information presented after encoding. On the other hand, items that are cued are protected from such interference. This notion is in line with the proposition that cued items represent the focus of attention in working memory, whereas the last item does not (Niklaus, Singmann, & Oberauer, 2017).

5. Feature-Based Attentional Weighting and Spreading in Visual Working Memory

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Authors' contributions

MN Review of the literature, design of the research question, design of the study, programming with Matlab, data collection, data analysis and interpretation, writing of the manuscript.

KN Supervision and discussion of MN's contributions, revision of manuscript.

FvE Supervision and discussion of MN's contributions, revision of manuscript.

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5.1. Abstract

Attention can be directed at features and feature dimensions to facilitate perception. Here, we investigated whether feature-based-attention (FBA) can also dynamically weight feature-specific representations within multi-feature objects held in visual working memory (VWM). Across three experiments, participants retained coloured arrows in working memory and, during the delay, were cued to either the colour or the orientation dimension. We show that directing attention towards a feature dimension (1) improves the performance in the cued feature dimension at the expense of the uncued dimension, (2) is more efficient if directed to the same rather than to different dimensions for different objects, and (3) at least for colour, automatically spreads to the colour representation of non-attended objects in VWM. We conclude that FBA also continues to operate on VWM representations (with similar principles that govern FBA in the perceptual domain) and challenge the classical view that VWM representations are stored solely as integrated objects.

5.2. Introduction

Attention pertains to the fundamental cognitive process of prioritizing relevant over irrelevant information and is, as such, critical for adaptive behavior (Posner, 1980). Whereas attention has been studied in its many forms for many decades in the perceptual domain, it has more recently become clear that attention also continues to operate on mental representations held in visual working memory (VWM) (Griffin & Nobre, 2003; Souza & Oberauer, 2016). Retro-cue studies have directed attention to select a particular object in VWM, either by directing attention to a spatial location (Griffin & Nobre, 2003) or by using non-spatial retro-cues such as an object's colour (Pertzov et al., 2013) shape (Li & Saiki, 2015) or category (Lepsien & Nobre, 2007). Here, we investigated whether another form of attention also continues to operate during VWM, namely: feature-based attention (FBA), which describes the deployment of attention to relevant feature values (e.g. blue) or feature dimensions (e.g. colour) within objects, and independent of spatial location (Maunsell & Treue, 2006). Specifically, we address whether FBA retro-cues can up- and down-regulate relevant and irrelevant features within multi-feature objects in VWM.

Modulation of performance in VWM tasks by FBA would be incompatible with the notion that integrated objects serve as the unit of VWM representations (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). This standard account has already been challenged by the finding that errors in the recall of different features of objects in VWM can be independent; even when one feature of a multi-feature object is shown to be forgotten, another feature may still be recalled (Bays, Wu, & Husain, 2011; Fougnie & Alvarez, 2011). Furthermore, ecological arguments can be proposed for attention to continue to operate in VWM at the feature level, since keeping multiple features per object is costly (Fougnie, Asplund, & Marois, 2010; Oberauer & Eichenberger, 2013; Olson & Jiang, 2002). We hypothesize, therefore, that FBA is capable of dynamically weighting feature representations within objects held in VWM.

In addition to attention to specific feature attributes, it has become clear that FBA can also be directed at dimensions (Fanini, Nobre, & Chelazzi, 2006; Found & Müller, 1996; Müller et al., 1995). The potential relevance of a feature-dimension level has recently also been postulated for VWM, in the form of a dimensional feature-bundle model (DFB) (Töllner et al., 2015), which contains a layer that represents entire feature dimensions in addition to lower level specific feature stores whose attributes are bound at the higher object-level (Brady & Alvarez, 2011). Based on these observations, we hypothesize FBA may not only affect WM representations by facilitating individual feature representations, but perhaps also by weighting entire feature dimensions - possibly by up-regulating neuronal excitability in brain areas processing a particular feature dimension (Chawla, Rees, & Friston, 1999; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990; Jonides, Lacey, & Nee, 2005; Pasternak & Greenlee, 2005). A prediction that follows from this work is that the hypothesized biasing effect of FBA in VWM will be stronger if, for different mnemonic objects, attention is directed to features within the same dimension, in comparison to across different dimensions.

An interesting characteristic of FBA in the perceptual realm is its global nature. That is, processing of an attended feature attribute (Saenz, Buracas, & Boynton, 2002; Treue & Trujillo, 1999) or dimension (Gledhill et al., 2015; McAdams & Maunsell, 2000) is enhanced throughout the visual field, independent of the spatial focus of attention. Based on this work, we finally hypothesized that the influence of FBA in VWM may similarly be a global influence that will automatically spread to other (uncued) objects, with regard to their feature representations in the same dimension.

We thus set out to investigate three key hypotheses. First, features within multi-feature objects can be flexibly up- and down-regulated based on current relevance. Second, FBA in VWM is most efficient if directed within the same dimension for different objects. Third, feature dimension weighting spreads automatically to non-attended objects in VWM. To this end, we employed a series of VWM tasks that deployed FBA retro-cues and required a continuous reproduction of the colour or orientation of probed objects.

5.3. Methods

5.3.1. Participants.

Across three experiments, we recruited three separate groups of healthy volunteers. Experiment 8 included twenty-one participants (11 females, age: M = 24, Range = 19-38). One participant was excluded because she reported closing her eyes during the working memory delay (thereby not processing the retro-cues). Experiment 9 included another pool of twenty participants (13 females, age: M = 22, Range = 18-29) and so did Experiment 10 (10 females, age: M = 25, Range = 18-39).

Experimental protocols received approval from the Central University Research Ethics Committee of Oxford. The experiment was conducted in accordance with their policy on research involving human participants and personal data. All participants provided informed consent, had normal or corrected-to-normal vision and reported normal colour vision. Participation was reimbursed £8 per hour. All three experiments each lasted 75 minutes and participants were debriefed after participation.

5.3.2. Materials.

The experiments were presented on a 23-inch monitor (1920 x 1080, 60 Hz) using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) in Matlab. Throughout the experiments, the background colour was set to grey (RGB = .78,.78,.78). Stimuli consisted of coloured arrows (length: 1.50°, width: 0.50°visual angle), at a viewing distance of 70 cm. For each trial, orientations were drawn randomly without replacement from 360 possible angles, and colours were drawn randomly without replacement from 360 colours created from the CIE L*a*b* colour model. The model's luminance parameter was set to 70, a∗ and b∗ were set to 20 and 38 respectively.

5.3.3. Experimental procedures.

Each trial (Figure 14 for a schematic) began with the presentation of a central fixation cross for 500 ms, followed by the display of the study array containing three coloured arrows for 500 ms. The arrows were presented equidistantly on an invisible circle (diameter 4.91°) centered around fixation. The location of the three arrows varied randomly on a trial-to-trial basis. After a 750 ms delay, a retro-cue was presented for 300 ms centrally 2.35°above the fixation cross. In the cued condition either the word "colour" or "angle" was presented, and in the neutral condition the word "both" was displayed. Retro-cues cueing either feature dimension were valid in 75% of the cases, and only informed which dimension was most likely to be probed (i.e. in contrast to typical retro-cueing studies, cues never informed which object was most likely to be probed). Probes were presented 1500 ms after the retro-cue and contained two relevant pieces of information. First, at the locations where the arrows had been presented, three circles (diameter: 0.90°) were presented, of which one was filled. This filled circle indicated which object was probed. Second, a response wheel was presented centered on the probed location (diameter: 12.28°-14.53°, centered 2.46°away from screen center). The nature of the wheel indicated the dimension that had to be reported: a blank and a coloured wheel prompted an orientation and a colour recall, respectively. Participants responded using a computer mouse that controlled the wheel's handle (length: 0.50°), whose initial position was randomly assigned. Response time was unlimited until participants moved the handle, which triggered the count-down of a 2500 ms dial up time, which was visualized by a sand clock (length and width: 1°). The position of the handle when participants clicked or when the time limit was reached was taken as the response. At the end of each trial, feedback on the performance in the trial (reproduction precision, re-scaled as a number between 0 and 100) was displayed for 250 ms. After a blank 500-ms inter-trial interval, the next trial started.

The experiment consisted of ten blocks, which were separated by self-paced breaks. A total of 432 trials were run after an initial completion of eight practice trials, which were discarded from analyses.

The feature dimensions colour and orientation were probed an equal number of times. In a fifth of all trials, a neutral cue was displayed. For the remaining trials, the feature dimension was cued with 75% validity, yielding 144 validly cued, 48 invalidly cued, and 48 neutral trials for each of the two task dimensions. All trial types were randomly interleaved.

5.3.4. General data analysis.

For each trial we collected one main dependent variable: the angular response deviation in either colour or orientation space between the participant's report and target object's true feature value. For both dimensions, response deviations ranged between -180°and 180°and were converted into an absolute value, which we term "error". For several control analysis, we also investigated response times, defined as the time between the onset of the probe screen and the start of the (time restricted) dial-up, which was triggered by movement of the mouse. All analyses were based on participant-specific condition averages. Trials with a response onset time above 4s were discarded from analyses. Conditions were compared using an analysis of variance (ANOVA), as implemented in the afex package (Singmann, Bolker, & Westfall, 2015) in R. Throughout the manuscript, degrees of freedom are Greenhouse-Geisser corrected in ANOVAs for repeated-measures factors with more than two levels. Furthermore, following Bakeman's (Bakeman, 2005) recommendations, we report η_g^2 as an effect size measure for ANOVAs. Follow-up contrasts are obtained using the methods implemented in lsmeans (Lenth & Hervé, 2015). For ANOVAs, these contrasts use Satterthwaite approximated degrees of freedom. To control for multiple testing, p-values of post-hoc contrasts are corrected using the Tukey's HSD method and are denoted p_{hsd}. The data and the analysis scripts for all experiments can be accessed in the Open Science Framework (https://osf.io/cz7xt/).

5.4. Experiment 8: Feature-Dimension-Based Retro-Cues Improve Representations in the More Relevant Feature Dimension, at the Expense of the Less Relevant Feature Dimension

In Experiment 8, participants held three coloured arrows in memory and were probed to reproduce either the colour or orientation of one of them after a delay on a continuous wheel (Figure 14a). A filled black circle indicated the probed item and the nature of the wheel determined the dimension that had to be reported: a blank and a coloured wheel prompted an orientation and a colour recall, respectively. Participants responded using a computer mouse that controlled the wheel's handle. We measured the absolute error between the true and the reported value in degrees. While the objects were held in VWM, either an informative retro-cue was presented, which indicated the feature dimension that was most likely going to be probed (without informing which object would most likely be probed), or a neutral retro-cue was presented. We expected to find better working memory performance when the dimension was validly cued, in comparison to when the dimensional cue was neutral or invalid. To assess this hypothesis, the means of participants' reproduction errors (absolute deviation from the target colour/orientation in degrees) were submitted to a 3 (cue validity: valid, neutral, invalid) x 2 (dimension: colour, orientation) repeated-measures analysis of variance (ANOVA).

Figure 14b depicts the mean errors in degrees for valid, neutral and invalid cues, separately for the colour and orientation dimensions, and suggests an inverse relationship between errors and the probability of being probed in a certain dimension. The analysis of errors yielded a main effect of cue validity [$F(1.6, 29.6) = 8.11, p = .003$, $\eta^2_g = .039$]. Post-hoc contrasts revealed lower mean errors for valid than for invalid cues [$t(38) = -4.03, p_{hsd} < .001$], whereas the comparisons between valid vs. neutral cues [$t(38) = -2.07, p_{hsd} = .109$] and neutral vs. invalid cues [$t(38) - 1.95, p_{hsd} = .138$] were not significant. Importantly, however, in line with the claim that valid and invalid cues are associated with a benefit and cost in working memory performance, respectively, the linear contrast for the effect of validity was also significant [$t(38) = 4.03, p < .001$]. This was further confirmed by an alternative approach to investigating the benefits and costs of dimensional cues, as depicted in Figure 14c. For this analysis, we calculated a single normalized benefit as the difference between the mean error in valid and neutral cues per dimension, and then averaging across the two dimensions. Similarly, a single normalized cost was

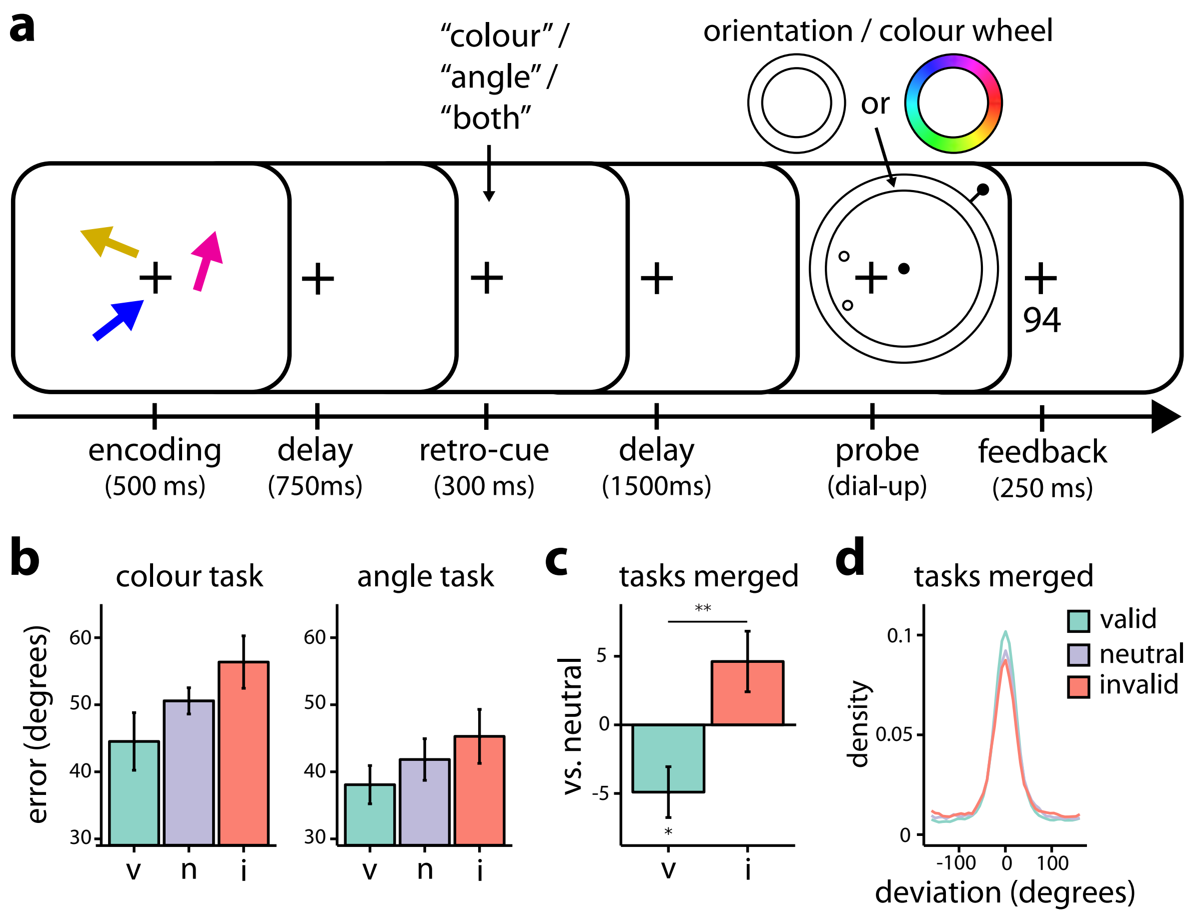

Figure 14: **Procedure and results Experiment 8. (a)** Experimental procedure. After encoding three coloured arrows, either an informative retro-cue (the word "colour" or "angle") was presented that indicated with 75% validity which feature dimension was going to be probed, or a neutral retro-cue (the word "both") was presented that indicated that either feature dimension was equally likely to be probed. Retro-cues were informative for all objects, and individual objects remained equally likely to be probed. Participants reported the dimension indicated by the nature of the wheel for the object indicated by the filled circle (right upper object in schematic), followed by performance feedback on a scale from 0 (bad) to 100 (perfect). **(b)** Mean errors for valid (v), neutral (n) and invalid (i) cues for the colour and orientation dimensions (N = 20). Errors bars depict 95% within-subjects confidence intervals (c29). **(c)** Data were normalized by subtracting the average value in the neutral condition from the valid and invalid conditions before averaging these data between the colour and the orientation tasks. Asterisks indicate significant results of a one-sample t-test of normalized benefits (v, valid - neutral) and costs (i, invalid - neutral) against zero, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. Error bars depict ± 1 standard error of the mean (SEM). **(d)** Density plot of response deviations relative to the probe's true feature value, averaged across dimensions, for the different cueing conditions.

defined as the difference in errors between invalid and neutral cues. One sample t-tests against zero yielded a significant benefit [$t(19) = -2.64, p = .016$], a nearly significant cost [$t(19) = 2.09, p = .050$], and a significant difference between benefit and cost, [paired $t(19) = -3.27, p = .004$].

We also compared performance on both dimensions and found better performance in reporting the orientation in contrast to the colour dimension [$F(1, 19) = 8.51$, $p = .009$, $\eta^2_g = .049$]. Despite this difference, however, the effects of cue validity did not differ across the two dimensions, as indicated by a non-significant interaction between validity and dimension [$F(1.9, 35.2) = 1.04$, $p = .359$, $\eta^2_g = .002$].

The response-deviation density plots in Figure 14d reveal that the uncued dimension was not dropped, but instead that the effects of FBA retro-cues in VWM operate in a subtle manner on the fidelity of representations. Taken together, these results indicate that FBA can enhance VWM representations in the more relevant feature dimension, and suggest that this occurs at the expense of the less relevant feature dimension.

5.5. Experiment 9: Retro-Cueing Benefits are Larger when Cued Feature Dimensions are Shared Between Objects

In Experiment 9 (see Figure 15a for a trial-schematic), we always presented two, instead of three, coloured arrows, that were always presented on the left and right side of the fixation cross (distance from center: 2.46°). After a 750 ms delay, two retro-cues were simultaneously presented for 500 ms, one at each arrow's location. The letter "C" or "A" was presented to indicate that the colour or the angle of this arrow would have to be reported (100% valid), if this arrow would be probed (50% chance for each arrow). In the same-dimension condition, the same letter was displayed for both objects (A-A and C-C). In the different-dimension condition, one object was cued colour and the other angle (A-C and C-A). In the neutral condition, two "X"s were displayed to indicate that all dimensions of the objects could be tested. The remaining sequence of events was the same as in Experiment 9.

The experiment consisted of ten blocks, which were separated by self-paced breaks. A total of 468 trials were run after an initial completion of ten practice trials, which were discarded from analyses.

The feature dimensions colour and orientation were asked to be reported an equal number of times. Neutral, same-dimension and different-dimension retro-cues were presented an equal number of times and the feature dimension cue was 100% valid, yielding 78 trials per cue condition and dimension. All trial types were presented in random order.

It has been proposed that VWM access is easier when the to-be-remembered features of all objects are in the same dimension. Based on this work, in Experiment 9 we investigated whether the same principle applies to the allocation of attention. To this end, we modified the cueing procedure of Experiment 8 as depicted in Figure 15a. For each of the two presented memory stimuli, we separately presented a feature-dimension retro-cue that indicated with 100% certainty which feature dimension would be tested, if that object would be probed (50% chance per object). The critical manipulation here was that both objects would be cued either with regard to the same dimension, or with regard to different dimensions. Directing attention within the same dimension was expected to be associated with a larger retro-cueing benefit. To investigate this hypothesis, a 3 (cue type: same, different, neutral) x 2 (dimension: colour, orientation) repeated-measures ANOVA was performed on means of participants' errors.

Figure 15b depicts the mean errors for all experimental conditions (Figure 15d for the associated density plots). Relative to neutral retro-cues, both same and different dimension retro-cues benefited performance, with this benefit being strongest when the cued feature dimensions are shared between the two objects. This is supported by a significant main effect of cue type [F(1.4, 27.4) = 17.25, $p < .001$, $\eta_g^2 = .056$], with post-hoc contrasts confirming a cueing benefit for same vs. neutral cues [$t(38) = -5.87$, $p_{hsd} < .001$], as well as for different vs. neutral cues [$t(38) = -2.98$, $p_{hsd} = .013$]. Crucially, same cues were additionally associated with a larger benefit than different cues [$t(38) = -2.89$, $p_{hsd} = .017$]. Figure 15c again depicts the normalized benefits relative to the neutral conditions and confirms a significant benefit for same [$t(19) = -4.84$, p < .001] as well as for different cues [$t(19) = -2.82$, $p = .011$], with a significant difference between them [paired $t(19) = -4.50$, $p < .001$]. Moreover, while the main effect of dimension [$F(1, 19) = 20.96$, $p < .001$, $\eta_g^2 = .126$] again revealed better performance on reporting the orientation than colour dimension, cue type and dimension did not interact with one another [$F(2.0, 37.7) = 0.77$, $p = .470$, $\eta_g^2 = .004$], indicating that the effects of cue type did not differ across the two dimensions.

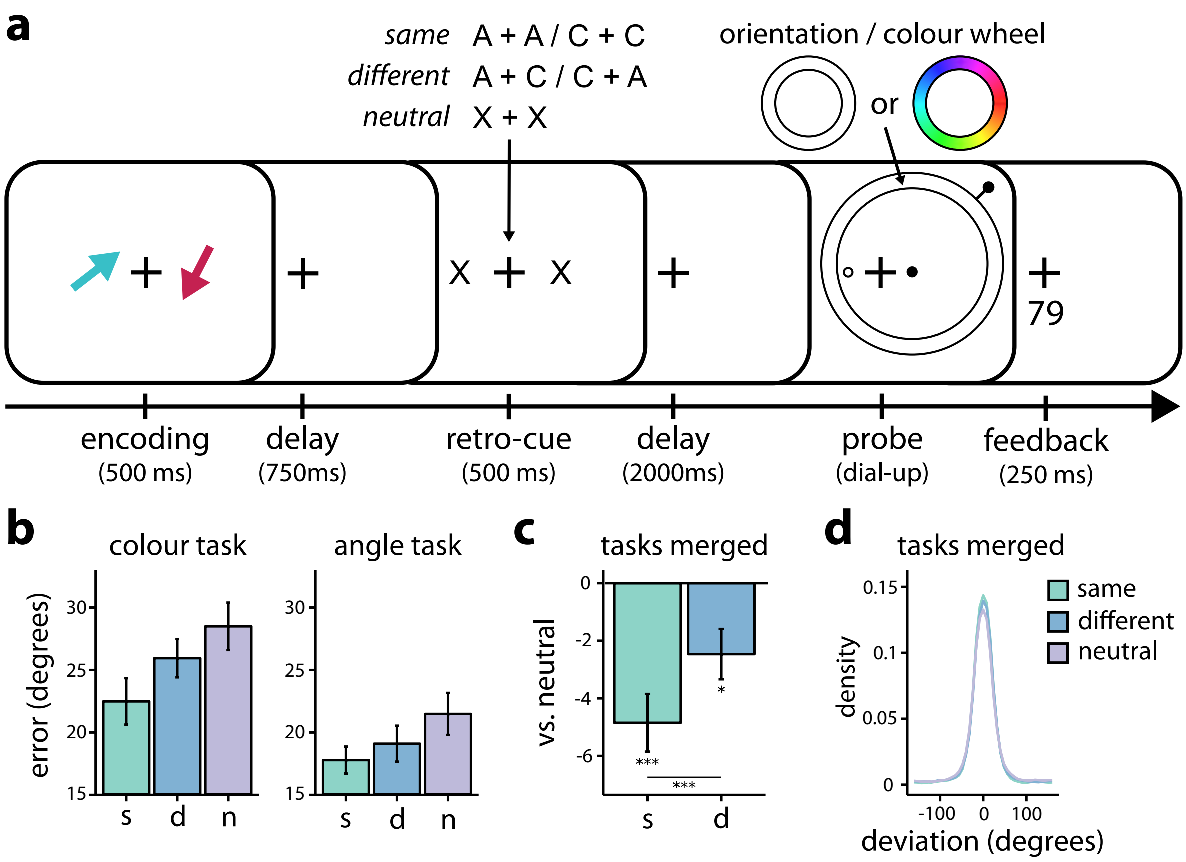

Figure 15: **Procedure and results Experiment 9.** **(a)** Experimental procedure. For each of the two encoded coloured arrows, either a neutral retro-cue ("X", 33%) was presented, or a retro-cue that indicated which feature dimension (A = angle, C = colour) would be tested, if that object would be probed. In the same condition (33%), both objects were cued with regard to the same dimension, whereas in the different condition (33%), each object was cued with regard to a different dimension. Response procedure as in Experiment 8. **(b)** Mean errors for same (s), different (d) and neutral (n) cues for the colour and orientation dimensions (N = 20). **(c)** Normalized benefits for same (s, same - neutral) and different (d, different - neutral) cues. **(d)** Density plot of response deviations in all cueing conditions. Conventions as in Figure 14.

It is conceivable that participants required additional time to process and utilize the attentional cues when these were directed across two in comparison to within one dimension. If at time of probe presentation such processes are finished for same- but not for different-dimensional cues, then this may lead to additional interference and thereby worsen performance following different-dimensional cues. To investigate this possibility, we reasoned that this would result in delayed onset of the reproduction report for different dimension trials. Importantly, paired t-tests revealed that response-onset times for same (M_{colour} = 1.38 s, $M_{orientation}$ = 1.17 s, SD_{colour} = 0.37, $SD_{orientation}$ = 0.39) and different (M_{colour} = 1.33 s , $M_{orientation}$ = 1.14 s, SD_{colour} = 0.36, $SD_{orientation}$ = 0.37) cues did not differ, neither for the colour [paired $t(19) = 1.38$, $p = .183$] nor for the orientation dimension [paired $t(19) = 0.67$, $p = .512$].

Taken together, these results demonstrate that there is an additional benefit if attention can be directed to the same, as opposed to different feature dimensions for different objects in VWM.

5.6. Experiment 10: Feature-Dimension-Based Attentional Weighting of Colour Spreads to the Colour of Non-Cued Objects

5.6.1. Methods.

A schematic sequence of events on each trial is depicted in Figure 16a. Until presentation of the first retro-cue, the procedure is identical to Experiment 8 (and so are all stimuli dimensions). The first retro cue was presented for 500 ms and presented either the letter “C” or “A” at a location to indicate that the colour or angle would be probed, if this object would be tested early. Items that would not be probed early were marked by “X” (as depicted in Figure 16a). After a 1500 ms delay, either the cued object was probed on the cued dimension, or a second cue was presented at a previously uncued object’s location indicating which dimension and object were going to be tested instead, after an additional delay. This second retro-cue was presented for 500 ms and followed by a 1500 ms delay before the response wheel appeared. In contrast to Experiments 8 and 9, the response wheel was always coloured and thus only the cue indicated the dimension that had to be reported for the probed arrow, which was again identified by a filled dot appearing at the location of where the object had been presented. From the outset of a trial, all objects were equally likely to be probed. Accordingly, the chance of being probed initially was 33%, whereas the chance of receiving another retro-cue instead was 66%. The critical manipulation was that in those trials that received a second retro-cue (for a previously uncued object), either the same or a different dimension was cued (with same and different retro-cues being equally probable). Thus, while in these "late" trials participants were always required to shift their attention to another object, in half the trials they were additionally required to shift their attention to another feature-dimension, whereas in the other half of the trials they maintained their attention in the same feature-dimension.

In half the trials, two (instead of only a single) objects were retro-cued at the stage of the first retro-cue. In these trials, retro-cues always indicated the same dimension, and the chances of being probed initially or receiving another retro-cue reversed to 66% and 33%, respectively. To increase sensitivity, we collapsed trials across the number of early retro-cues. This was further justified by the lack of an interaction between the number of retro-cues presented early, and the congruency of the second retro-cue, with regard to the performance in the "late" trials of interest [$F(1,19) = 0.02$, $p = .895$, $\eta_g^2 < .001$].

The experiment consisted of ten blocks, which were separated by self-paced breaks. A total of 432 trials were run after an initial completion of 20 practice trials, which were discarded from analyses. The feature dimensions colour and orientation were asked to be reported an equal number of times. All trial types were randomly interleaved.

To investigate whether the global nature of FBA also extends to VWM, in Experiment 10 we asked participants to keep track of the cued feature associated with a specific object in order to report it on a combined colour and orientation wheel (Figure 16a). Sometimes participants were probed on the initially cued feature ("early"), but other times a second retro-cue cued participants to switch their attention towards the same or different dimension of another object, in which case they were probed "late". We focused on performance on late trials, and expected better performance when the second retro-cue was directed towards the same compared to a different feature dimension. A 2 (congruency: same, different) x 2 (dimension: colour, orientation) repeated measures (ANOVA) was performed on subject means of errors.

Figure 16b shows the mean reproduction errors for late trials when attention was redirected to a feature dimension that was the same or different to the dimension indicated by the first cue, separately

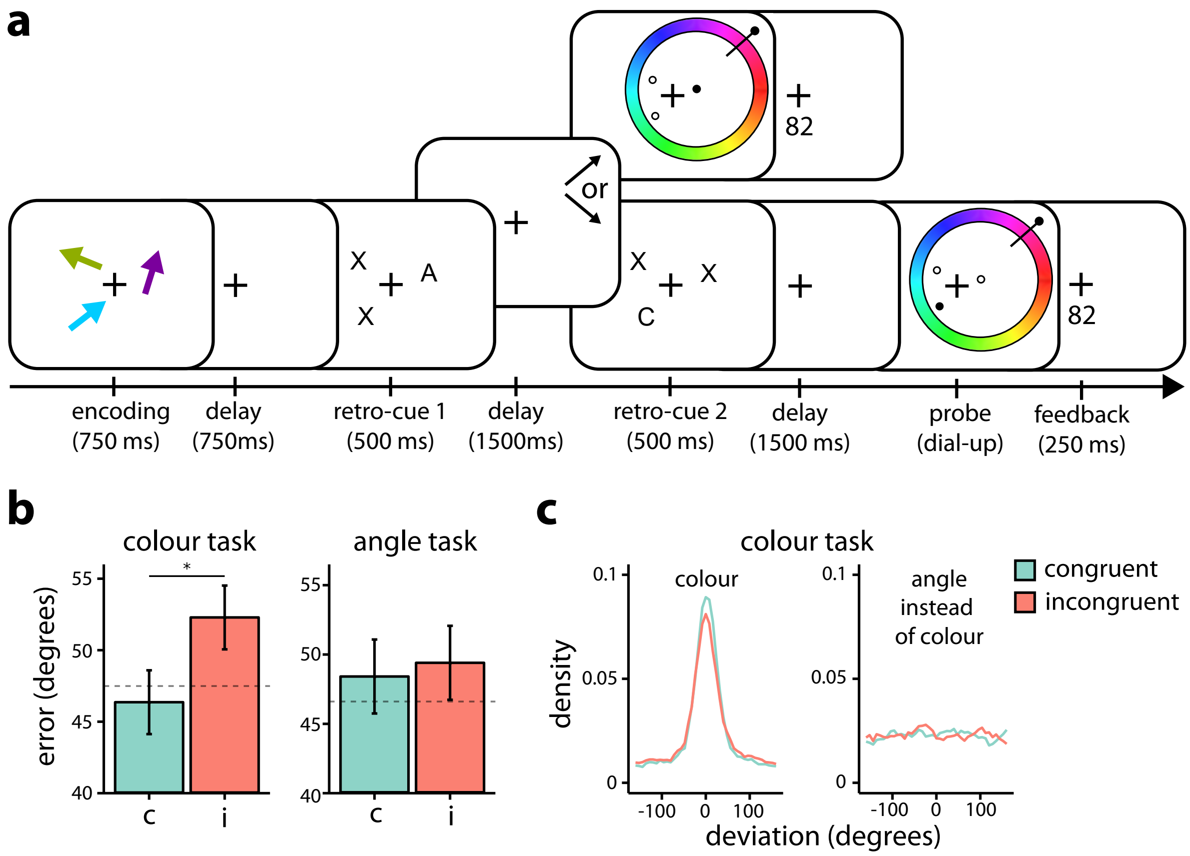

Figure 16: **Procedure and results Experiment 10.** **(a)** Experimental procedure. After encoding three coloured arrows, a retro-cue indicated which feature dimension (A = angle, C = colour) would be tested if the object would be probed "early". Presentation of an "X" indicated that this object would not be probed immediately. In some trials, instead of probing "early", a second retro-cue was presented that directed attention towards a feature of a previously uncued ("X") object in "late" trials. The dimension cued with the second retro-cue could either be same as (50%) or different from (50%) the dimension cued with the first retro-cue. Participants were required to report the cued dimension for the object identified by the filled circle on a combined colour and orientation wheel. In half the trials, two (instead of one) "early" retro-cues were presented, but analyses collapsed across the number of early retro-cues (see Methods for details). **(b)** Mean errors in late trials for the colour and orientation dimension as a function of dimensional congruency between the second retro-cue and the first retro-cue (N = 20). The dashed black line shows the mean performance in early trials. **(c)** Density plot of response deviations in the colour dimension relative to the probed object's true colour (left) or true orientation (right), for same and different trials. Conventions as in Figure 14.

for the colour and orientation dimension. In line with the notion of an automatic spread of FBA, the error analysis yielded a main effect of congruency (same / different) [$F(1, 19) = 4.98$, $p = .038$, $\eta_g^2 = .009$] driven by better performance for same in comparison to different trials. Moreover, neither the main effect of dimension [$F(1, 19) = 0.04$, $p = .838$, $\eta_g^2 = <.001$] nor the interaction between dimensions and congruency [$F(1, 19) = 1.95$, $p = .178$, $\eta_g^2 = .005$] reached significance. However, despite the absence of a significant interaction between dimensions and congruency, it appears from Figure 16b that the congruency effect is mostly driven by performance on the colour dimension. Indeed, dimension specific analyses yielded a congruency effect for the colour [$F(1, 19) = 7.73$, $p = .012$, $\eta_g^2 = .026$] but not for the orientation dimension [$F(1, 19) = 0.15$, $p = .702$, $\eta_g^2 <.001$].

Interestingly, for the colour dimension, we observed that performance in same trials was not statistically different from performance on early trials in which the colour dimension was probed [paired $t(19) = 0.58$, $p = .563$] (with the latter performance being indicated by the dashed line in Figure 16b). In contrast, different trials showed worse performance [paired $t(19) = 2.49$, $p = .022$]. Thus, even though attention had to be re-directed to another object, if this refocusing of attention occurred within the same feature dimension, no significant cost was observed.

In order to verify our interpretation, it is important to rule out two additional possible sources that may contribute to the observed pattern in behaviour. First, because both dimensions were required to be reported on the same wheel, erroneously reporting the wrong dimension may occur. If so, it is feasible that this may occur more frequently in different trials in which the to-be-reported dimension changes with the second retro-cue. Focusing on the colour dimension data in which the effect was most pronounced, Figure 16c depicts response deviations relative not only to the to-be-reported colour (left panel), but also to the not-to-be-reported orientation (right panel). Critically, these data reveal no evidence for erroneously reporting the object's orientation in the colour task, nor for any difference between same and different trials with regard to such misreporting. Second, shifting to another dimension on different trials may take time, and if the probe would appear before such shifting was completed, increased interference may be expected by the probe onset. To address this concern, we again turned to our response-onset time data. Critically, paired t-tests indicated that response-onset times in the colour dimension did not differ between same ($M_{colour} = 0.61$ s, $SD_{colour} = 0.21$) and different ($M_{colour} = 0.59$

s , $SD_{colour} = 0.21$) trials [paired $t(19) = 1.12$, $p = .276$].

These results indicate that if attention is directed towards the colour of one specific object in VWM, this automatically facilitates the colour representations of the other objects in VWM - in line with a spread of FBA at the dimensional level.

5.7. General Discussion

Over the past decade, retro-cueing has become a powerful paradigm for studying the influence of attention over internal representations held in VWM (Souza & Oberauer, 2016). To date, however, this work has concentrated predominantly on retro-cues that allow for the selection of one out of several mnemonic representations (whose features are typically thought to be part of an integrated object-based representation). In a series of visual working memory tasks, we investigated the effects of feature-based retro-cues that cued either the colour or the orientation dimensions across multi-feature objects held in VWM. We show that FBA also continuous to operate on VWM representations, by improving VWM representations in the cued feature dimension, at the expense of the uncued dimension. Moreover, we demonstrate that attentional allocation is most efficient if, for different objects, FBA is directed within the same dimension in comparison to across different dimensions. Finally, we found that, at least for the colour dimension, attentional weighting operates in a global manner, spreading automatically to the colour representation of non-attended objects maintained in VWM. These findings parallel global FBA modulations observed in perception (Gledhill et al., 2015; McAdams & Maunsell, 2000; Saenz et al., 2002; Schledde et al., 2016; Treue & Trujillo, 1999). Because these data suggest that features can be independently prioritized to enhance performance, they also challenge the dominant view that the unit of VWM representation consists solely of integrated objects.

5.7.1. Features and feature-dimensions of VWM representations.

Based on the observation that VWM capacity for single feature objects was similar to memory capacity for multi-feature objects, VWM was proposed to operate on integrated object representations (Luck &

Vogel, 1997; Vogel et al., 2001). Recent studies, however, have started to challenge this view by demonstrating that increasing the number of features per object is costly (Fougnie et al., 2010; Oberauer & Eichenberger, 2013) and proposing that feature dimensions of multi-feature VWM objects may be stored with some degree of independence (Zokaei, Heider, & Husain, 2014) while being bound together by attention (Luck & Vogel, 2013). Consistent with the proposition of independent storage buffers, errors in reporting the colour and orientation of an object in VWM can arise largely independently in each feature dimension (Bays, Wu, & Husain, 2011; Fougnie & Alvarez, 2011). Complementing this work on forgetting, we here show attention can also be voluntarily deployed to facilitate performance for relevant feature-dimensions in order to best serve goal-directed behaviour.

Although we did not systematically manipulate working memory load, our results also have bearings on the debate regarding whether VWM capacity is governed by slots or a flexible resource (Bays & Husain, 2008; Ma, Husain, & Bays, 2014; Suchow, Fougnie, Brady, & Alvarez, 2014). Clearly, a very strict slot model, in which the unit of each slot is an integrated object, cannot account for our results. Indeed, our results may more readily be explained by resource models (Awh, Barton, & Vogel, 2007; van den Berg, Shin, Chou, George, & Ma, 2012) in which resources can be flexibly allocated to the attended at the expense of the unattended feature dimension. Still, we cannot exclude less stringent forms of slot models that incorporate some type of resource and/or feature-specificity within the slots (Xu & Chun, 2006; Ye, Hu, Ristaniemi, Gendron, & Liu, 2016).

Our findings converge with dimensional effects observed in perception as well as VWM (Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Töllner et al., 2015). However, it should be noted that such dimensional effects do not necessarily justify a "representational" dimension-layer (Töllner et al., 2014), as conceptually no extra representational information is provided. Indeed, any object like a green car can be fully characterized by its object- and feature level attributes. However, as we will argue in the next section, the proposition of independent stores for feature dimensions may still be well suited for explaining the dimensional effects that we and others (Bays, 2014; Fougnie & Alvarez, 2011; Töllner et al., 2014, 2015) observed, especially when considering the potential neuronal mechanisms behind FBA in VWM.

5.7.2. Potential neuronal basis of dimensional effects.

Both Fougnie and Alvarez (Fougnie & Alvarez, 2011) as well as Bays (Bays, 2014) postulated that the independence they observed for performance on different features of multi-feature objects in VWM may reflect the fact that the feature level representations of a given object are supported by distinct neural populations. Accordingly, feature-specific errors may be attributable to stochastic noise at the level of feature-specific neuronal stores (Fougnie & Alvarez, 2011). It is conceivable that our retro-cues were particularly helpful for overcoming this “noise” within those neuronal populations tuned to the relevant feature dimension. In line with this speculation, attention has been shown to decrease noise correlations in populations coding for relevant stimuli (Cohen & Maunsell, 2009; Mitchell, Sundberg, & Reynolds, 2009), as well as stimulus features (Cohen & Maunsell, 2011).

To accommodate for the dimensional effects observed in the current experiments, it is interesting to consider that FBA in the perceptual domain has been shown to modulate neuronal population that are specialized for processing a particular feature dimension, such as visual area V4 for colour and V5/MT for motion (Chawla et al., 1999; Corbetta et al., 1990; McAdams & Maunsell, 2000; Schledde et al., 2016). Moreover, the same targeted sensory areas support VWM (Jonides et al., 2005; Pasternak & Greenlee, 2005; Serences, Ester, Vogel, & Awh, 2009). Although not directly tested in the current experiment, such modulations provide a plausible neural basis for two particular effects we observed in the current study: (1) the enhanced cueing benefit when objects were cued in the same feature dimension in Experiment 9, and (2) the automatic spread of attention to the cued feature dimension (ic. colour) of non-attended objects in Experiment 10. FBA directed at only one population may be more efficient than directing FBA across two different populations, and up-regulation of the processing efficiency of the entire population may lead to the automatic spread of attentional biasing to non-attended objects, within the feature dimension that is coded for by that neuronal population. Finally, we speculate that this neural account may also explain why we observed a much more prominent spreading of attention for colour, as compared to orientation information in Experiment 10. Colour involves a higher-level visual attribute that is likely to have a more dedicated neuronal population, such as area V4. Orientation, in comparison, is a visual attribute that is much more tightly linked with retinotopic coordinates, and it is not evident that any particular visual area beyond the primary visual cortex is dedicated for processing this feature dimension. To further test these speculative ideas, in future work, it would be interesting also to investigate the automatic spreading of feature-dimension-based attention to non-attended objects for other feature dimensions such as motion, contrast, and shape (Fougnie & Alvarez, 2011).

5.7.3. Relation to previous FBA studies in VWM.

Whereas ample evidence exists for retro-cueing particular objects in VWM, previous evidence for an effect of dimension-based retro-cues has been scarce and ambiguous. In one recently published study by Pilling and Barrett (2016), retro-cueing a feature dimension yielded no effect on performance in a change-detection task, whereas retro-cueing-benefits were observed for a sameness detection. In the present task, we used a continuous reproduction task and demonstrate that the influence of feature dimension based retro-cues in VWM is robust, for both colour and orientation dimensions. Moreover, in parallel to our study, a recently published study with a similar task to our first experiment also reported that FBA can affect VWM performance, showing an increased rate of recalling the target item for valid in comparison to neutral dimension based retro-cues (Ye et al., 2016). Here, we further show that such a FBA benefit comes with a cost for the non-cued dimension, that it may operate in a global manner, and that it is larger when the cued feature-dimension is shared between objects. Interestingly, in yet another related study, it was shown that attention to particular feature dimensions during a working memory task (in this case, by retrieving particular dimensions), may also impact the consolidation of information into long-term memory 48. This suggests that the FBA effects on VWM that we observed here during VWM delay, may not only have a facilitatory influence in the short term, but may even carry-over to long-term memory benefits of relevant features. Future work is required to test this exciting possibility.

5.7.4. Sources of errors.

Following up on our demonstration that FBA can influence VWM performance, a logical next step will be to investigate the sources of errors contributing to these effects. Error distributions can be modeled as a mixture of three components (Bays, Catalao, & Husain, 2009), which allows the estimation of the proportion of trials in which participants (a) recalled the probed item, (b) recalled a non-probed item from the memory list, or (c) guessed. Moreover, the model allows the estimation of the precision with which memory items are held. Due to the restricted numbers of trials per condition we were cautious about performing such analyses given the possibility of obtaining unreliable estimates of the relevant factors. Future research should aim to pursue this question by using a simpler design that allows for more trials per condition.

5.7.5. Conclusion.

We have shown that FBA continues to operate on VWM representations. In line with our three key hypotheses, we demonstrated that directing attention to feature dimensions of multi-feature VWM objects is associated with a benefit as well as a cost for relevant and irrelevant feature representations respectively. Moreover, in line with dimensional effects that are characterized best in the perceptual domain, we showed that FBA is most efficient if directed at the same dimension for all cued objects. Finally, in line with global influences of FBA in the perceptual domain (Gledhill et al., 2015; McAdams & Maunsell, 2000; Saenz et al., 2002; Treue & Trujillo, 1999), we revealed that attentional weighting of the colour dimension automatically spreads to the colour of non-attended objects in VWM. A plausible explanation for these observations is that FBA operates at the level of the neuronal populations that specialize in the processing of relevant feature dimensions.

Appendices

A. Study 1

A.1. Experiment 1

A.1.1. Model Based Analysis Experiment 1 Based on Negative Probes

Median parameter values, their 95% CI, and the results from all pairwise comparisons among conditions for each parameter for the negative probes are reported in Table 6.

A.1.2. Negative Trials - Last Item Benefit

We obtained no credible differences between the experimental conditions for the rate parameter and thus focused on comparing conditions of the intercept parameter.

New probes that were presented in the center of the screen cannot be associated with any serial position if no retro-cue was presented. Hence, no last-item benefit can be computed for these probes. To test the last-item benefit for retro-cued new probes, we compared the mean intercept for serial positions 1 to 5 with the mean intercept for serial position 6 for retro-cued probes. This comparison indicated that there was somewhat ambiguous whether or not the retro-cued serial position 6 had a smaller intercept than serial positions 1 to 5 ($p_B = .07, 59.1$ ms [-6.4, 151.9]). We additionally report all pairwise comparisons between cued serial positions in Table 6.

Moreover, aggregated across all cued serial positions, we found a smaller intercept for cued than for non-cued probes ($p_B < .001$, 79.2 ms [48.2, 113.0]).

A.1.3. Negative Trials - Asymptote

We also investigated the effects of serial position and cue condition on the asymptote parameter of the SAT model. For retro-cued probes, we found a lower (i.e. stronger) asymptote for serial position 6 in comparison to serial positions 1 to 4 (all $p_B < .05$), but not serial position 5 ($p_B = .18$). We found credible retro-cue benefits for the asymptote, when all non-cued probes were compared to all retro-cued probes

Table 6: Median group-level parameters for Experiment 1 based on negative probes

	Cued SP 1	Cued SP 2	Cued SP 3	Cued SP 4	Cued SP 5	Cued SP 6	Non Cued
				Intercept			
δ	$0.30^{ab}_{[0.23,0.34]}$	$0.27^{ac}_{[0.18,0.33]}$	$0.29^{abc}_{[0.22,0.34]}$	$0.25^{ac}_{[0.16,0.31]}$	$0.25^{ac}_{[0.18,0.33]}$	$0.21^{c}_{[0.12,0.27]}$	$0.34^{b}_{[0.32,0.36]}$
				Rate			
β	$4.04^{a}_{[2.38,5.54]}$	$3.09^{a}_{[1.81,4.56]}$	$3.43^{a}_{[2.16,4.84]}$	$3.00^{a}_{[1.67,4.56]}$	$2.90^{a}_{[1.65,4.29]}$	$3.06^{a}_{[1.82,4.56]}$	$4.47^{a}_{[3.17,5.46]}$
				Asymptote			
λ	$-2.14^{ab}_{[-1.58,-3.00]}$	$-1.93^{ab}_{[-1.46,-2.56]}$	$-1.93^{ab}_{[-1.48,-2.63]}$	$-1.97^{ab}_{[-1.49,-2.72]}$	$-2.60^{ac}_{[-2.09,-3.33]}$	$-3.39^{c}_{[-2.47,-4.65]}$	$-1.60^{b}_{[-1.34,-1.89]}$

Note. Values are based on negative probes. We report the 95% CI interval in square brackets for the three parameters of the SAT function based on all negative probes. Columns separate different retro-cued serial positions (SP). All non-cued negative probe trials are represented in the last column. Credible pairwise differences between conditions are displayed using a compact-letter display

($p_B < .001$, 0.76 [0.38, 1.16]). Finally, when all retro-cued probes were compared to all non-cued probes separately, we found credible retro-cue benefits for serial positions 4 ($p_B = .001$) and 5 ($p_B < .001$), but not for serial positions 1 to 3 (all $p_B > .082$).

A.2. Experiment 2

A.2.1. Analysis based on intrusion probes.

After discarding 1,000 warmup samples, we retained 3,000 post-warmup samples for each of 4 independent chains. Convergence statistics indicated good mixing behavior with $\hat{R} \leq 1.01$ for all estimated model parameters (Gelman & Rubin, 1992). Visual inspection of MCMC trace plots of the group-level parameters indicated the same. The number of effective samples was above 300 for all estimated model parameters. Model fits are depicted in Figure 17, which compares the median of the model predictions generated from the posterior distribution (the lines) to the observed proportions of "accept" responses (the dots), for positive and intrusion probes separately. Visual inspection of the model fit shows that the model struggled to account for the retrieval dynamics of intrusion probes. Median parameter values, 95% CIs, and results of all pairwise differences between experimental conditions are reported in Table 7. We also compared the retro-cue benefit of serial position 5 with each earlier serial position individually. Figure 18 reports the p_B values for these comparisons and shows that none of these comparisons provides credible evidence for an attenuation of the retro-cue benefit (smallest $p_B = .51$).

Table 7: Median group-level parameters for Experiment 2 based on intrusion probes

	SP 1	SP 2	SP 3	SP 4	SP 5
			Intercept		
δ_{NC}	$0.46^{ab}_{[0.37,0.56]}$	$0.59^{f}_{[0.51,0.67]}$	$0.49^{a}_{[0.42,0.56]}$	$0.46^{a}_{[0.40,0.54]}$	$0.34^{bd}_{[0.24,0.42]}$
δ_{RC}	$0.18^{cde}_{[0.00,0.30]}$	$0.29^{cd}_{[0.17,0.38]}$	$0.25^{cde}_{[0.14,0.34]}$	$0.18^{ce}_{[0.05,0.27]}$	$0.10^{e}_{[-0.10,0.23]}$
			Rate		
β_{NC}	$3.55^{a}_{[1.75,5.76]}$	$4.84^{a}_{[2.73,7.45]}$	$3.62^{a}_{[1.95,5.72]}$	$3.43^{a}_{[1.83,5.65]}$	$3.67^{a}_{[1.84,5.75]}$
βRC	$2.88^{a}_{[1.31,5.04]}$	$3.71^{a}_{[1.72,6.35]}$	$3.09^{a}_{[1.41,5.30]}$	$2.94^{a}_{[1.51,4.70]}$	$4.88^{a}_{[2.37,8.10]}$
			Asymptote		
λ_{NC}	$2.61^{ab}_{[1.72,3.63]}$	$1.86^{a}_{[1.15,2.70]}$	$2.23^{ab}_{[1.54,3.06]}$	$2.84^{b}_{[1.94,3.77]}$	$4.93^{c}_{[3.80,6.12]}$
λ_{RC}	$2.44^{ab}_{[1.56,3.43]}$	$1.84^{a}_{[1.09,2.68]}$	$2.42^{ab}_{[1.66,3.24]}$	$2.91^{b}_{[2.15,3.75]}$	$4.54^{c}_{[3.43,5.67]}$

Note. We report the 95% CIs in square brackets. Columns separate different serial positions (SP). Non-cued and retro-cued probes are reported in separate rows and are denoted with subscripts NC and RC respectively. Credible pairwise differences between conditions are displayed using a compact-letter display.

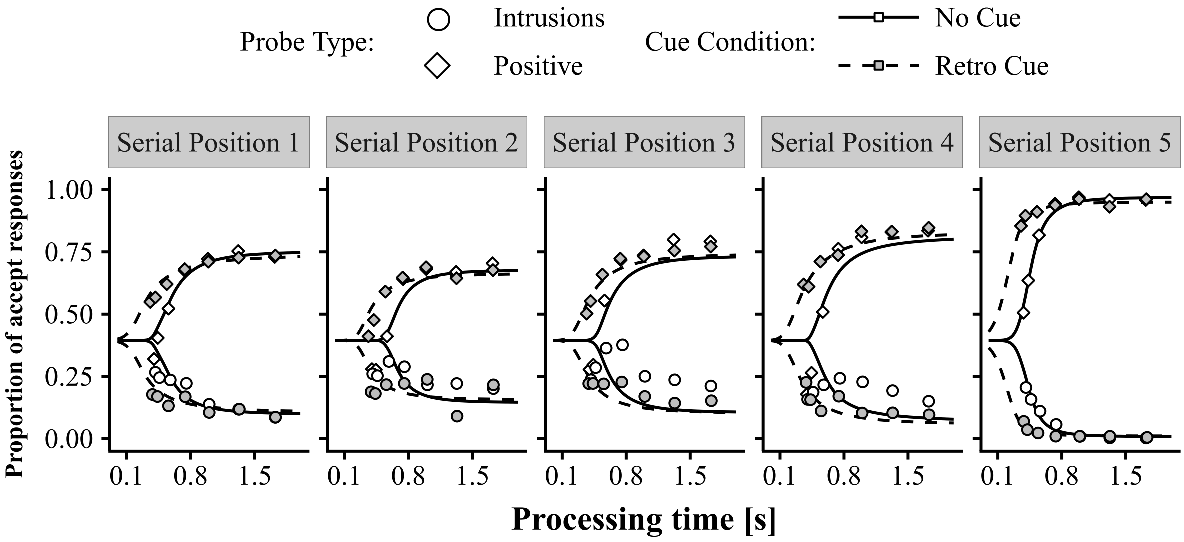

Figure 17: Observed (symbols) and predicted (lines) group-level proportion of accept responses for positive (diamonds) and negative (circles) probes for each serial position and cue condition as a function of processing times. Filled objects connected through a dashed line depict retro-cued trials whereas non-filled objects connected through a solid line depict non-cued trials.

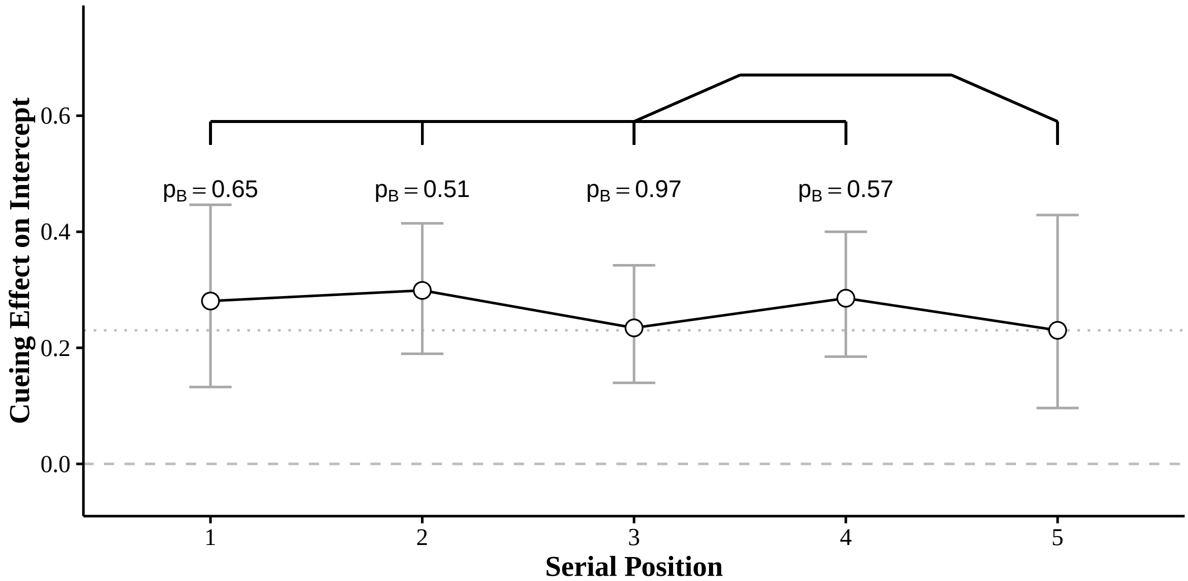

Figure 18: Median group-level posterior estimates for the retro-cue benefit in seconds for each serial position. p_B above serial positions 1-4 denotes the evidence for a difference of the cueing effect between this particular serial position and serial position 5. The dotted line depicts the median cueing effect for the last serial position. The dashed line indicates the absence of a cueing effect. Error bars depict 95% CI.

A.3. Experiment 3

A.3.1. Analysis based on intrusion probes.

Due to convergence issues, in this model we constrained the rate parameter to be the same across all serial positions and cue conditions. After discarding 1,000 warmup samples, we retained 3,000 post-warmup samples for each of 4 independent chains. Convergence statistics indicated good mixing behavior with $\hat{R} \leq 1.01$ for all estimated model parameters (Gelman & Rubin, 1992). Visual inspection of MCMC trace plots of the group-level parameters indicated the same. The number of effective samples was above 300 for all estimated model parameters. Model fits are depicted in Figure 19, which compares the median of the model predictions generated from the posterior distribution (the lines) to the observed proportions of "accept" responses (the dots), for positive and intrusion probes separately. Visual inspection of the model fit shows that the model struggled to account for the retrieval dynamics of uncued intrusion probes. Median parameter values, 95% CIs, and results of all pairwise differences between experimental conditions are reported in Table 8. We also compared the retro-cue benefit of serial position 5 with each earlier serial position individually. Figure 20 reports the p_B values for these comparisons and shows that none of these comparisons provides credible evidence for an attenuation of the retro-cue benefit (smallest p_B = .49).

Table 8: Median group-level parameters for Experiment 3 based on intrusion probes.

	SP 1	SP 2	SP 3	SP 4	SP 5
			Intercept		
δ_{NC}	$0.44^{a}_{[0.38,0.50]}$	$0.49^{a}_{[0.41,0.60]}$	$0.45^{a}_{[0.39,0.52]}$	$0.31^{d}_{[0.26,0.37]}$	$0.26^{d}_{[0.18,0.33]}$
δ_{RC}	$0.15^{b}_{[0.05,0.23]}$	$0.06^{bc}_{[-0.21,0.19]}$	$0.08^{bc}_{[-0.13,0.19]}$	$-0.06^{c}_{[-0.67,0.08]}$	$-0.10^{c}_{[-0.45,0.05]}$
			Rate		
β			$4.37_{[3.20,5.39]}$		
			Asymptote		
λ_{NC}	$1.82^{ab}_{[1.22,2.49]}$	$1.50^{b}_{[0.86,2.25]}$	$1.59^{b}_{[1.02,2.26]}$	$2.35^{c}_{[1.73,3.08]}$	$3.77^{d}_{[2.99,4.61]}$
λ_{RC}	$2.09^{ac}_{[1.48,2.79]}$	$1.67^{ab}_{[1.02,2.41]}$	$1.69^{ab}_{[1.09,2.38]}$	$2.53^{c}_{[1.90,3.26]}$	$3.91^{d}_{[3.11,4.72]}$

Note. We report the 95% CIs in square brackets. Columns separate different serial positions (SP). Non-cued and retro-cued probes are reported in separate rows and are denoted with subscripts NC and RC respectively. Credible pairwise differences between conditions are displayed using a compact-letter display.

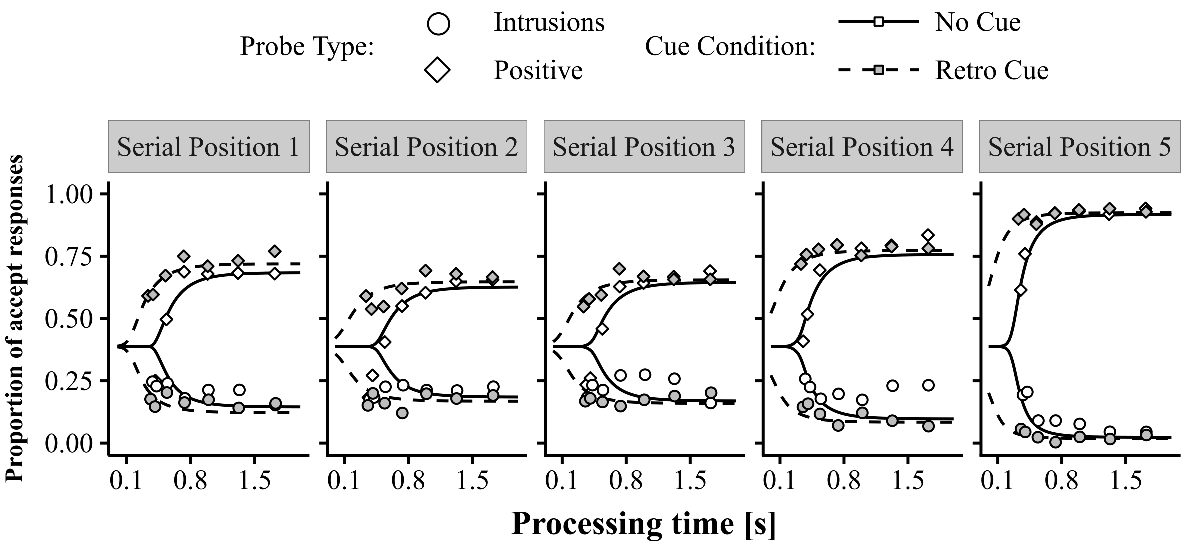

Figure 19: Observed (symbols) and predicted (lines) group-level proportion of accept responses for positive (diamonds) and negative (circles) probes for each serial position and cue condition as a function of processing times. Filled objects connected through a dashed line depict retro-cued trials whereas non-filled objects connected through a solid line depict non-cued trials.

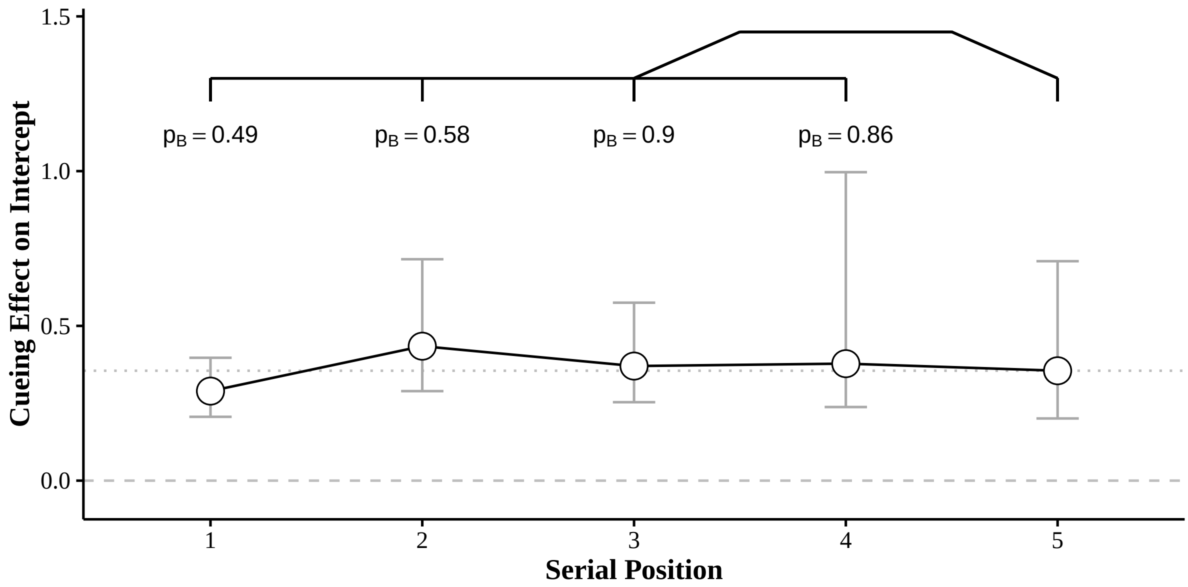

Figure 20: Median group-level posterior estimates for the retro-cue benefit in seconds for each serial position. p_B above serial positions 1-4 denotes the evidence for a difference of the cueing effect between this particular serial position and serial position 5. The dotted line depicts the median cueing effect for the last serial position. The dashed line indicates the absence of a cueing effect. Error bars depict 95% CI.

6. Acknowledgements

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[11]The order of names was determined by a random permutation in R (R Core Team, 2014).

7. Curriculum Vitae

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Curriculum Vitae

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Supervisors Prof. Dr. Klaus Oberauer and Prof. Dr. Stephan Lewandowsky (University of Bristol)

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2013–2017 **Student of PhD program**, *University of Zurich*, Zurich.
2011–2013 **MSc Psychology**, *University of Bern*, Bern.
2008–2011 **Bsc Psychology and Economics**, *University of Bern*, Bern.
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Fellowships

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Vocational Experience

2013–2017 **Student of PhD program**, *University of Zurich*.
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Detailed achievements:
- Presenting research at scientific conferences (talks and posters);
- Analysing complex data using hierarchical Bayesian methods
- Teaching undergraduates

2011–2013 **IT support**, *University of Bern, Division of Experimental Psychology and Neuropsychology*.
2007–2008 **Accounting clerk**, *Swiss Railways SBB*.

Computer skills

Languages	R, Python, Matlab, Stan,JAGS,BUGS,SPSS,Git
Data Base	MySQL, SAP
Formatting	LaTeX, Gimp, Inkscape
OS	Linux, Windows, Mac
MS Office	Word, Excel, PowerPoint

Languages

German	**Mother Tongue**
English	**Proficient**
French	**Good**
Spanish	**Beginner**

Publications

- Niklaus, M., Singmann, H. & Oberauer, K. (2017). A cross-eyed focus of attention? Additive last-item and retro-cue benefits. *Unpublished Manuscript*.
- Niklaus, M. & Oberauer, K. (2017). Vulnerability to suffix interference in working memory: Evidence for two distinct forms of prioritization. *Unpublished Manuscript*.
- Thalmann, M., Niklaus, M. & Oberauer, K. (2017). Estimating bayes factors for linear models with random slopes on continuous predictors. *Unpublished Manuscript*.
- Niklaus, M., Nobre, A. C. & Van Ede, F. (2017). Feature-based attentional weighting and spreading in visual working memory. *Scientific Reports*, *7*.
- van Ede, F., Niklaus, M. & Nobre, A. C. (2016). Temporal expectations guide dynamic prioritization in visual working memory through attenuated alpha oscillations. *Journal of Neuroscience*, 2272–16.
- Mensen, A., Gorban, C., Niklaus, M., Kuske, E. & Khatami, R. (2014). The effects of theta-burst stimulation on sleep and vigilance in humans. *Frontiers in Human Neuroscience*, *8*.

Teaching Experience

2017 **Experimental Training**, *University of Zurich*.
Bachelor course co-taught with Dr. Henrik Singmann.

2016 **Experimental Training**, *University of Zurich*.
Bachelor course co-taught with Dr. Henrik Singmann and Prof. Dr. Klaus Oberauer.

2014 **Supervision of Bachelor's thesis**, *University of Zurich*.
Tutored student: Samuel Winiger

2014 **Debates in Cognitive Psychology**, *University of Zurich*.
Master course co-taught in English with Dr. Alessandra Da Silva Souza de Carvalho

Miscellaneous

Assistant Jobs

2010–2011 **Research Assistant**, *General and Neuropsychology Unit University of Bern*.
Programming, conducting and analyzing cognitive experiments

Internships

2011 **Research Internship**, *Cognitive Psychology Unit University of Zurich*.
Programming, conducting and analyzing experiments

2010 **Research Internship**, *General and Neuropsychology Unit University of Bern*.
Programming, conducting and analyzing experiments

2009–2010 **Research Internship**, *Sleep Laboratory Klinik Barmelweid*.
Help with study involving electroencephalography measurements and transcranial magnetic stimulation

Civil Service

2014-2016 **Burgerbibliothek Bern**.

2012 **Bürgerspital Solothurn**.

Summer Schools and Peer Groups

2015–2017 **Member of Peer Mentoring Group Methods and Statistics**, *University of Zurich*.

2014 **Summer school on computational modeling of cognition**, *Laufen, Germany*.

2014 **Member of Peer Mentoring Group Applied Programming for Psychologists**, *University of Zurich*.

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